U.S. 101 MP 142.48 HARLOW CREEK (WDFW ID 990548): Preliminary Hydraulic Design Report

~~Julie Heilman PE, State Hydraulic Engineer~~
~~WSDOT Headquarters Hydraulics Office~~

~~Mike (Rocky) Hrachovec~~Eleanor Bartolomeo PE, Project Manager
Stream Design Engineer
FPT20-0~~6949~~7379
Natural Systems Design

Aaron Lee, Staff Hydraulic Engineer EIT
FPT20-05353
Natural Systems Design

Scott Katz, Project Geomorphologist
FPT20-35854
Natural Systems Design

~~Beth Rood PE, Project Manager~~
~~HDR Engineering, Inc.~~

~~**Shaun Bevan PE, Senior Water Resources Engineer**~~
~~**HDR Engineering, Inc.**~~

~~**Rachel Ainslie, Water Resources EIT**~~
~~**HDR Engineering, Inc.**~~

~~**Ian Welch, Biologist**~~
~~**HDR Engineering, Inc.**~~

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January~~S~~~~October~~~~eptember~~ 202~~0~~~~1~~2

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1 Introduction

To comply with United States et al. vs. Washington et al. No. C70-9213 Subproceeding No. 01-1 dated March 29, 2013 (a federal permanent injunction requiring the State of Washington to correct fish barriers in Water Resource Inventory Areas [WRIAs] 1–23), the Washington State Department of Transportation (WSDOT) is proposing a project to provide fish passage at the United States Highway 101 (U.S. 101) crossing of Harlow Creek, tributary to the Queets River at Mile Post (MP) 142.48. This existing structure on U.S. 101 has been identified as a total fish barrier by the Washington Department of Fish and Wildlife (WDFW) and WSDOT Environmental Services Office (ESO) (site identifier [ID] 990548) and has an estimated 3,600 linear feet (LF) of habitat gain.

In accordance with~~Per~~ the injunction, and in order of preference, fish passage should be achieved by (1) avoiding the necessity for the roadway to cross the stream, (2) use of a full-span bridge, or (3) use of the stream simulation methodology. WSDOT evaluated the crossing using the unconfined bridge design methodology; this method was necessary because the stream is unconfined.

The crossing is located in Grays Harbor County on U.S. Highway 101, five~~5~~ miles east of the intersection with Clearwater Road, Washington, and 19 miles west of Lake Quinault, Washington and the U.S. 101 crossing of the Quinault River, in WRIA 21.~~–~~ The highway runs in an east–west direction at this location and the crossing is about 5.~~1~~ 6 miles upstream from the confluence of Harlow Creek with the Queets River based on the National Hydrography Database. Harlow Creek generally flows from southeast to northwest beginning about 3,900 feet (ft) upstream of the U.S. 101 crossing (see Figure 1 for the vicinity map).

The proposed project will replace the existing 4-foot-diameter corrugated metal pipe (CMP) culvert measuring 74.1 feet in length with a structure designed to accommodate a minimum hydraulic opening of 15 feet. A specific structure type ~~is not being recommended by Headquarters Hydraulics and~~ will be determined ~~by others~~ during future phases of the design. The proposed structure is designed to meet the requirements of the federal injunction using the unconfined bridge design criteria as described in the 2013 WDFW *Water Crossing Design Guidelines* (WCDG) (Barnard et al. 2013). This design also meets the requirements of the WSDOT *Hydraulics Manual* (WSDOT 2019).

This culvert crossing is located within~~on~~ the Quinault Indian Nation Reservation. As a result, some information readily available for other culvert crossings is ~~missing~~not available. For example, the Federal Emergency Management Agency (FEMA) has not performed a flood hazard analysis in this area, and the United States Geological Survey (USGS) has not done a soils analysis. This Preliminary Hydraulic Design (PHD) Report was prepared using~~with~~ all available information~~ available~~, and other sources of information have been used in place of those generally used in other PHD reports.

The draft report of the preliminary hydraulic design (PHD) was prepared by HDR, Inc. (HDR) in 2020. WSDOT received review comments on the Draft PHD from Washington Department of Fish and Wildlife (WDFW) and Quinault Tribe (Tribe). As part of Kiewit's Coastal-29 Team of the US 101/SR 109 Grays Harbor/Jefferson/Clallam, Remove Fish Barriers Project under a Progressive Design-Build (PDB) contract between Kiewit and WSDOT, Natural Systems Design (NSD) reviewed the draft PHD report, updated the hydraulic modeling and design, addressed WDFW and Tribe comments, and prepared the Draft Final PHD report. Responses to WDFW and Tribe comments are included in Appendix J~~K~~.

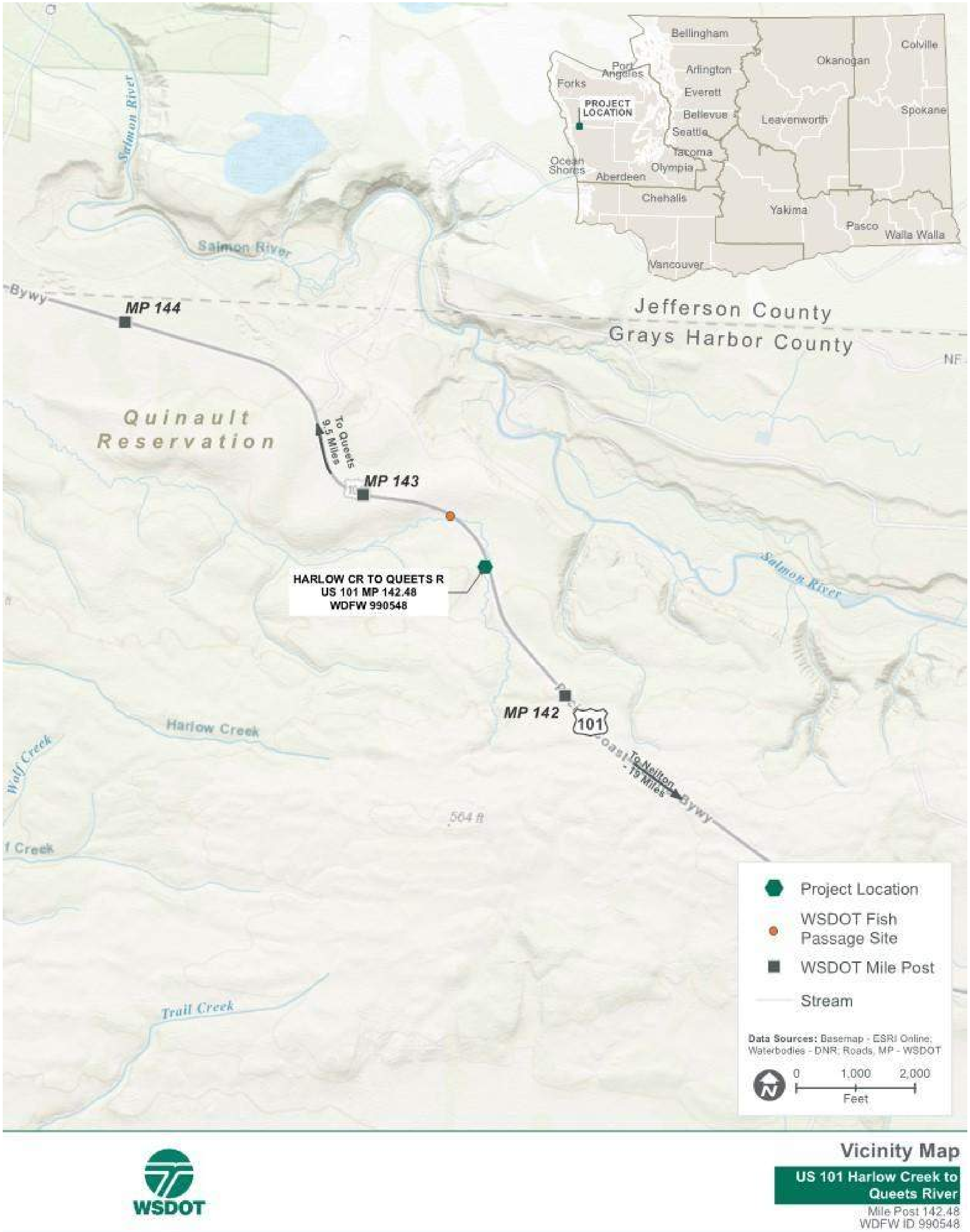


Figure 1: Vicinity map

2 Watershed and Site Assessment

The existing site was assessed in terms of watershed, land cover, geology, floodplains, fish presence, ~~observations,~~ wildlife, and geomorphology. This assessment was performed using desktop research including aerial photo analysis~~s;~~, resources such as USGS, FEMA, and WDFW~~;~~, and past records including~~like observation~~ field surveys, maintenance records, and fish passage evaluations.

2.1 Watershed and Land Cover

Harlow Creek drains into the left bank of the Queets River approximately 5~~.2~~ miles downstream of the U.S. 101 culvert outlet.~~is a left bank tributary to the Queets River, with the confluence located downstream of the creek's U.S. 101 culvert outlet~~. Harlow Creek consists of approximately 5.8 miles of stream length. Watershed area was measured at MP 142.48 as 200 acres (0.31 square mile) using Arc Hydro. This is the watershed for the MP 142.48 crossing only, not the entirety of Harlow Creek. The watershed is relatively flat with an average slope of 4.7 percent; none of the basin is characterized by slopes greater than 30 percent. According to StreamStats, the basin is 41 percent covered by canopy (USGS 2016). The basin is densely forested and interspersed with logging activities.

Figure 2~~Figure 2~~ shows the National Land Cover Database (NCLD) map. The breakdown of land cover within the watershed is in Table 1. The basin is primarily evergreen forest~~ at 76 percent~~.

Table 1: Percent of Basin Coverage by Land Cover Class

Land cover class	Basin coverage (percent)
Evergreen Forest	76.4
Low intensity developed	5.5
Scrub/shrub	16.4
Mixed forest	0.9
Herbaceous	0.5
Open space developed	0.5

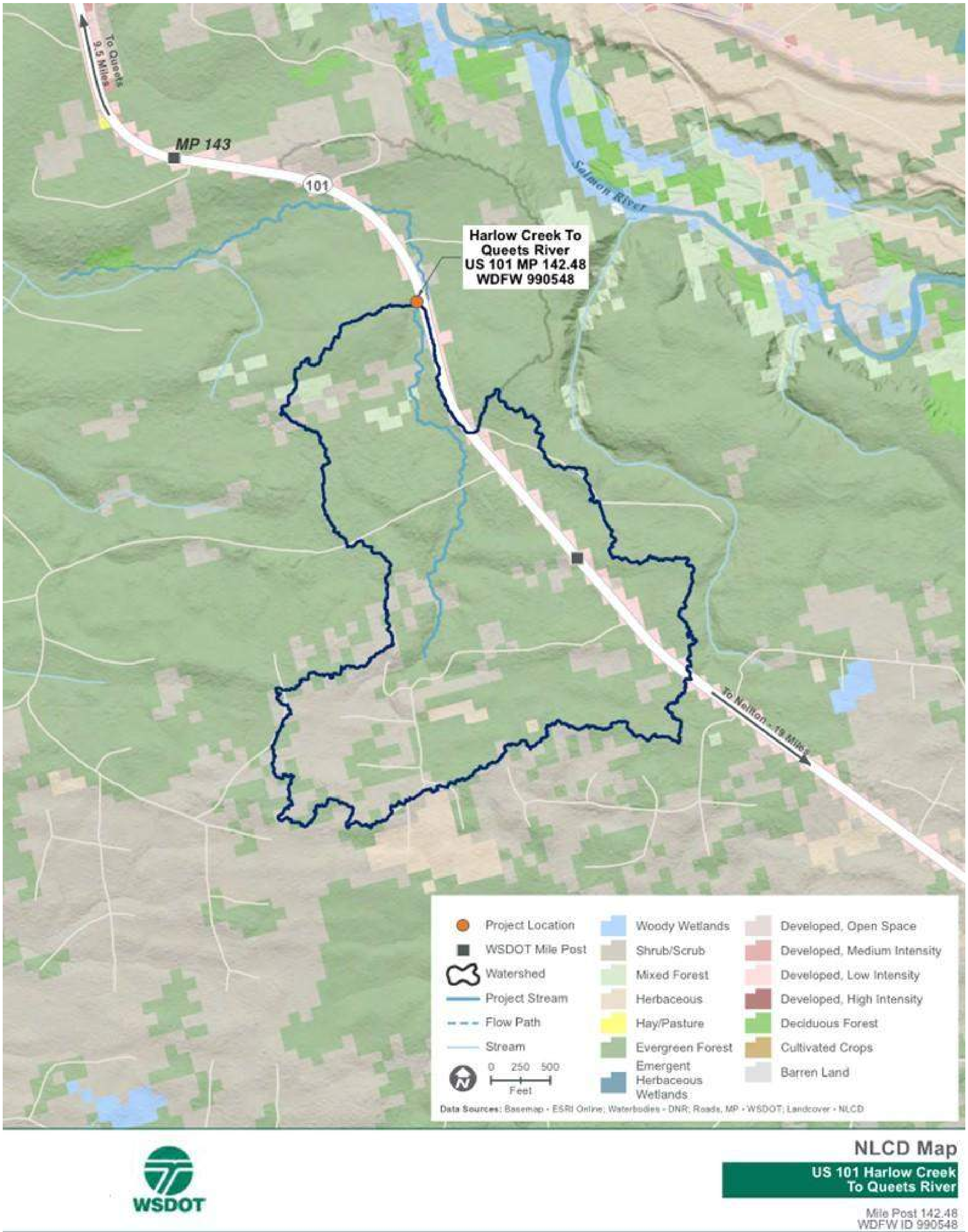


Figure 2: Land cover map

Aerial photographs of land cover dating from 1939 to 1996 accessed through the ArcGIS Living Atlas show the advent of logging activities at the site. The 1939 photo in Figure 3~~Figure 3~~ shows that little to no logging or development was present in the area. However, by the 1996 photo in Figure 4~~Figure 4~~, logging activities and development have cleared the forest in some areas.

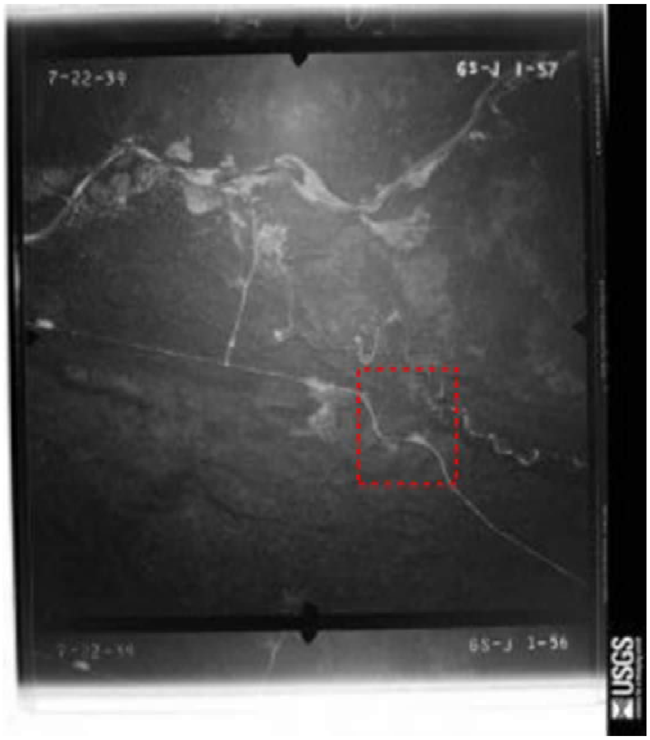


Figure 3: 1939 aerial photograph of project site

Figure 4: 1996 aerial photograph of project site

2.2 Geology and Soils

Geologic units in the watershed are summarized from 1:100,000 quadrangle mapping by USGS (Gerstel and Lingley 2000) and obtained from the Washington State Department of Natural Resources (DNR) Geologic Information Portal. The geology of the watershed for this project site is comprised of ~~comprises~~ the geologic units described below and referenced in Figure 5~~Figure 5~~. The entire basin is mapped as alpine glacial drift (Qapwt(2m)) and (Qapwo(2)).

- **Qapwt(2m):** Pleistocene Age, alpine glacial till, pre-Wisconsinan (Pleistocene alpine glacial drift)
  - Undifferentiated till and outwash; outwash consists of sand and gravel with lacustrine silt and clay; till is locally capped by loess; clasts are composed primarily of lithofeldspathic and feldspatholithic sandstone and basalt
- **Qapwo(2):** Pleistocene Age, alpine glacial outwash, pre-Wisconsinan (Pleistocene alpine glacial drift)
  - Sand and gravel composed of lithofeldspathic and feldspatholithic sandstone and basalt derived from the core of the Olympic Mountains

The Natural Resources Conservation Service (NRCS) Web Soil Survey cannot be used to summarize soils and geology at this crossing because ~~it~~the project is located on tribal lands and as a result no data are available.

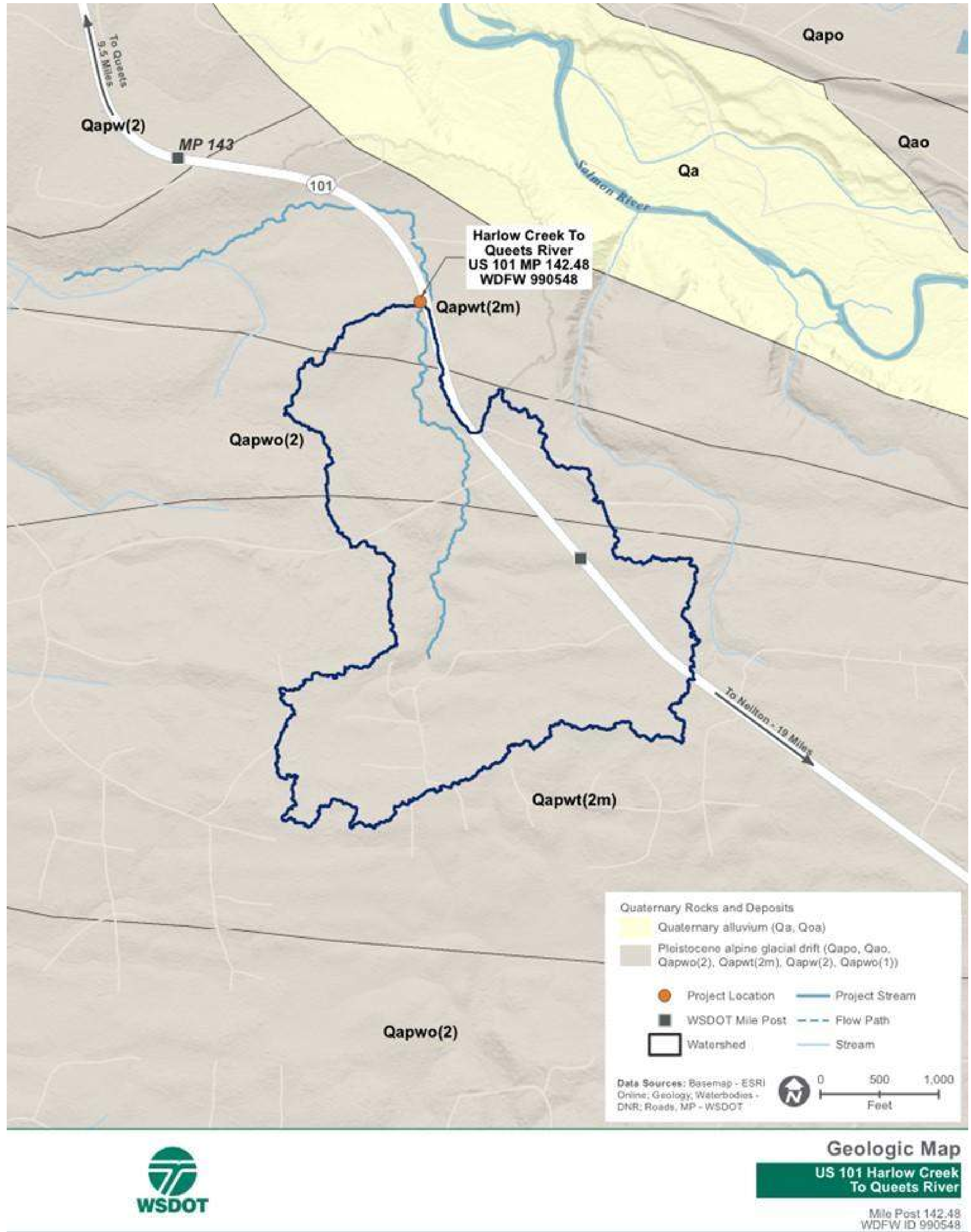


Figure 5: Geologic map

2.3 Floodplains

The project site is located on the Quinault Indian Nation Reservation and is not included in the Flood Insurance Study (FIS) for Grays Harbor County. A separately published FIS for the Quinault Indian Nation Reservation was not available at the time of preparing the PHD. ~~FEMA has not performed an analysis in this location to determine if t~~Thus, the project is not located within a regulatory Special Flood Hazard Area, (~~the~~with a 1 percent or greater annual chance of flooding in any given year) based on the available data. The crossing is located well outside of the floodplain of the Salmon River, ~~a~~the nearest river with a mapped floodplain, located less than two miles east of Harlow Creek. The crossing is also outside of the Queets River floodplain. No other information on flooding history of the site such as maintenance or historical records has been provided.

2.4 Site Description

The existing culvert at U.S. 101 MP 142.48 was documented by WDFW ~~to~~ having~~e~~ a 0 percent passability rating because of a water surface drop at the culvert outlet. The outlet of the pipe drops 0.9 foot to the channel bed downstream of the existing crossing, making it impassable to fish (WDFW 2014, WDFW 2019). ~~Fish habitat is negatively affected because it is difficult for the fish to travel upstream through the drop.~~ In addition, the structure has a slope of 3.28 percent according to the WDFW database report (the WSDOT survey measures it as 2.8 percent; see Section 2.7.2), a second criterion for 0~~%~~ percent

- passage (WDFW 2019. Comments on the WDFW form identify that inside the culvert, the velocity was measured as 14 feet per second (ft/s) and the stream plunges on~~-~~to riprap below the outlet. ~~A velocity this high would cause a scour pool to form on the downstream end of the culvert and it would be difficult for fish to swim against this current.~~ The WDFW Fish Passage and Diversion Screening I~~I~~nventory (FPDSI) documents unresolved fish passage problems both upstream and downstream of the crossing (WDFW 2014). Further detail regarding the extent and location of these problems is not provided in this report, though it is known that there is a~~n~~ down~~up~~stream fish passage barrier at MP 142.68 that will be addressed and evaluated in ~~another~~ its respective PHD report. Additionally, another barrier ~~one~~ downstream ~~barrier~~ with WSDOT Site ID 990178 is being removed, and the new structure is currently in construction. The total length of habitat gain for this crossing is ~~1,0803,600~~ 3,600 feet (WDFW 2014).

This culvert is not considered to be a chronic environmental deficiency. ~~No m~~Maintenance records ~~were provided for this culvert~~obtained by WSDOT do not indicate previous issues at the existing crossing.

2.5 Fish Presence in the Project Area

~~Harlow Creek is a left bank tributary to the Queets River.~~ The Statewide Washington Integrated Fish Distribution (SWIFD) (2020)~~ and WDFW online databases~~, as well as StreamNet (2020), document biological evidence of coho salmon (*Oncorhynchus kisutch*) spawning and rearing in the lower reaches of Harlow Creek approximately 4.5 miles downstream of the project area. These databases do not have fish use data for the upper reaches of Harlow Creek in the project vicinity; however, upper Harlow Creek does meet the physical criteria for the presence of coho salmon, steelhead, searun cutthroat trout, and resident trout (WDFW 2014, WDFW 2019)~~.~~ A downstream habitat survey conducted by WDFW in 2014 documents physical evidence of spawning and rearing habitat just downstream of the culvert (WDFW

2014). Coho use in Harlow Creek downstream of the project area is also reported in the WRIA 21 Queets-Quinault stream catalog (Williams and Phinney 1975).

The Queets River is documented to contain all five Pacific salmon species as well as steelhead and bull trout (Quinault Indian Nation 2011, SWIFD 2020, WDFW 2020, StreamNet 2020). The small substrate (D50 = 1.3 inches), and limited number of deep pools and complex cover ~~limited stream characteristics~~ in~~size and limited habitat~~ in Harlow Creek, however, may~~likely~~ preclude~~s~~ ~~spawning of larger salmon species such as~~ Chinook (*Oncorhynchus tshawytscha*) ~~and steelhead (*Oncorhynchus mykiss*)~~ from using this stream~~, particularly in the upstream reaches where the project crossing is located~~. Bull Trout have more specific habitat requirements than most other salmonids, in particular they require cold water (46 ºF or below) for spawning and egg incubation, and abundant in-stream cover for rearing (Rieman and McIntyre 1993). They typically spawn and rear in the cold, clear tributaries in the upper portions of watersheds, and therefore are not expected to be present in this area of Harlow Creek since it is low in the Queets watershed.

Rearing~~ coho~~ juvenile~~s~~ coho and ~~potentially overwintering juvenile~~ steelhead may disperse upstream to reaches close to the project crossing. Steelhead that inhabit the Queets River are part of the Olympic Peninsula distinct population segment (DPS) and are not currently listed under the Endangered Species Act (ESA). The WDFW online fish passage database does not list any impassable barriers on the mainstem Harlow Creek between the downstream reaches where coho are documented, and upstream where the project is located;~~,~~ though as mentioned above, unresolved fish passage problems are noted in the 2014 report that may or may not have been corrected at the time of the writing of this report. Coastal cutthroat trout (*Oncorhynchus clarkii clarkii*) are also widespread throughout small streams in Washington and are likely also present in Harlow Creek. They prefer the uppermost portions of these streams and may exhibit several life history patterns. They~~, and~~ can be anadromous and rear in streams for two~~2~~ to ~~3~~three years~~,~~ or be resident and remain entirely in freshwater (Wydoski and Whitney 2003).

Table 2~~Table 2~~ provides a list of salmonid~~ fish~~ species that potentially occur in Harlow Creek and that c~~w~~ould be affected by the culvert crossing.

Table 2: Native fish species potentially present within the project area

Species	Presence (presumed, modeled, or documented)	Data source	ESA listing
Coho salmon (*Oncorhynchus kisutch*)	Presumed (documented downstream)	SWIFD 2020, WDFW 2020, Quinault Indian Nation 2011	Not warranted
Olympic Peninsula DPS[a] steelhead (*Oncorhynchus mykiss*)	Presumed (documented in Queets River)	SWIFD 2020, WDFW 2020, Quinault Indian Nation 2011	Not warranted

Coastal cutthroat (*Oncorhynchus clarkii clarkii*)	Presumed	SWIFD 2020, Quinault Indian Nation 2011	Not warranted

a. DPS = distinct population segment.

2.6 Wildlife Connectivity

The one-~~-~~mile segment that contains MP 142.48 ~~falls in~~ ranked ~~Medium~~ medium priority for Ecological Stewardship and Low priority for Wildlife-related Safety. Adjacent segments to the north and south ranked ~~Medium~~ medium for Ecological Stewardship and Low for Wildlife-related Safety. WSDOT has determined that in order to be eligible for a habitat connectivity analysis, fish barrier correction projects must either be located ~~fall~~ in or adjacent to a high priority road segment, or ~~a~~have been requested by a project team member ~~can request the~~for analysis. ~~and t~~Thus, this project is not eligible.

2.7 Site Assessment

The following sections describe the existing conditions of Harlow Creek as observed during the site visits conducted on July 28, 2020 and June 25, 2021.

2.7.1 *Data Collection*

WSDOT conducted a topographic survey in March 2020. The survey extends 240 feet upstream of the culvert, 230 feet downstream of the culvert, with ~~and~~ a total roadway survey length of 660 feet. Survey information generally includes locations of stream channels and overbank areas along the channel.

During the preliminary design phase of the project, HDR visited the project site on July 28, 2020, to measure the bankfull width (BFW) and collect pertinent information to support the basis of design. ~~The bankfull width concurrence meeting with HDR, WSDOT, WDFW, and a tribal representative has not yet been conducted to gain concurrence on BFWs and other design considerations because of COVID-19. Concurrence will be gained at a later date as restrictions are lifted.~~ This section describes field observations collected during the July 28, 2020 and June 25, 2021 site visits of Harlow Creek from upstream to downstream. The main findings of the field reports ~~is~~ are summarized ~~here~~ in the subsections below and the full reports can be found in Appendix B.

~~Before the site visit, BFWs were determined using modeling and survey information. During the site visit, three BFWs were taken with an average of 7.6 feet. BFW determination is discussed in detail in Section 2.8.2.~~

~~WSDOT provided survey in March 2020. The survey extends 240 feet upstream of the culvert, 230 feet downstream of the culvert, and a total roadway survey length of 660 feet. Survey information generally includes stream channels and overbank areas along the channel.~~ NSD conducted the second site visit on June 25, 2021, along with Osborn Consulting (OCI) and Kiewit staff, to identify the WSDOT survey limits in the field and verify observations and findings from the 2020 site visit. Previous BFW measurement locations were reoccupied and remeasured, as were pebble counts. Concurrence was reached on a BFW of 10.3 feet by WDFW and QIN on August 9, 2021. BFW determination is discussed in detail in Section 2.8.2.

Existing Conditions~~.~~

The existing structure is a 74.1-foot-long, circular, corrugated steel, 4-foot-diameter culvert. From the WSDOT survey, the culvert has a gradient of 2.8 percent with the inlet invert elevation at 351.6 feet and the outlet invert elevation at 349.5 feet. As-built drawings for this crossing were provided by WSDOT; however, they contained minimal information pertaining to Harlow Creek and the existing structure at MP 142.48. As described above in Section 2.4, the creek crossing has ~~re are~~ high velocities~~y~~ (approximately 14 ft/s) and unresolved fish passage problems both upstream and downstream. The crossing is listed in WDFW's database as being a total barrier for fish and blocking ~~a~~ biologically significant habitat.~~reach. As a current barrier it~~ The barrier reduces ~~limits~~ fish access to ~~fish~~ rearing habitat by 37,040 square feet (SF). Species expected to benefit from removing and replacing this culvert include coho, steelhead, sea run cutthroat, and resident trout. Local constraints are not apparent from aerial photos, topographic survey, or WDFW field reports. The culvert runs perpendicular to the road ~~based on the survey~~ and the stream begins to run parallel to the road downstream of the crossing. No obvious signs of maintenance activity were observed, and no local constraints or infrastructure were observed.

Upstream ~~**Reach**~~

The upstream area ~~reach~~ observed during the site visit consisted of three different reaches, from upstream to downstream: (1)~~ Mainstem Harlow Creek from the culvert inlet to the confluence~~ with the ~~unnamed tributary 2)~~ m~~M~~ainstem Harlow Creek upstream of~~above~~ the~~e~~ confluence with the unnamed tributary (UNT), (2) UNT left bank, and (3) mainstem Harlow Creek from the confluence to the culvert inlet~~and 3) Unnamed Tributary (UNT) to Harlow Creek Left Bank~~.~~–~~ Each reach is described below, and ~~shown in~~ ,Figure 30~~Figure 30~~ shows the stream network within the extent of the surveyed limits.

1.~~–~~ Mainstem Harlow Creek~~–~~ Upstream of Confluence with UNT

The detailed topographic survey includes 50 feet of Harlow Creek above the confluence with the UNT. The upper reach of Harlow Creek is narrow and marshy, with a substrate entirely made up of silt and fines (Figure 6).

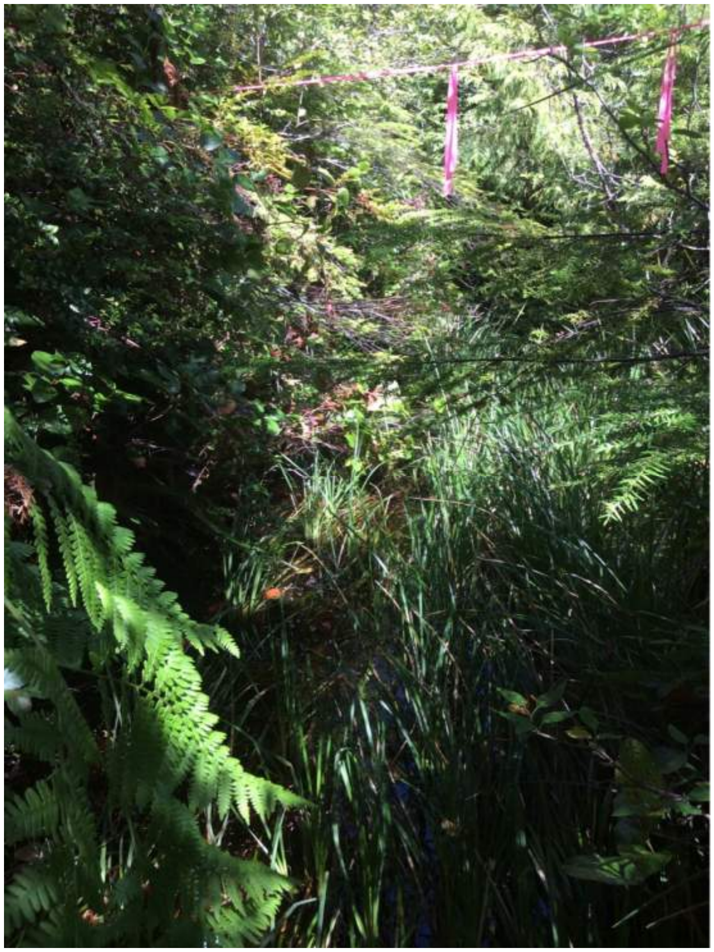


Figure 6: ~~Upper~~Mainstem Harlow Creek Upstream from Confluence

Sedges and brush are abundant on both banks. The banks are low, approximately 1 foot in height, and the channel is not well defined (Figure 7).

Figure 7: Substrate of ~~upper~~ Mainstem Harlow Creek Upstream from Confluence

The active floodplains are accessible, flat, and narrow; they are also terraced~~,~~ and slope up to a second floodplain that appears ~~inaccessible~~accessible only under extreme flood events. The large accumulation of logs in the upper mainstem channel are most likely the result of historic logging activities (Figure 8). At the confluence of the left bank UNT and mainstem, an accumulation of logs and fine sediment ~~aggradation~~ deposits ~~was~~were observed.

Figure 8: Large Woody Material (LWM) from historic logging

2.– UNT to Harlow Creek Left Bank

Detailed topographic survey of the UNT to Harlow Creek Left Bank ~~upstream~~ extends 40 feet upstream of the confluence with Harlow Creek.~~ ~~ At this location, a large stump lies across the channel with ferns and shrubs growing out of it (Figure 9). Flow goes under and around the stump.

Figure 9: Mid channel stump in UNT to Harlow Creek Left Bank

The channel substrate at this location is made up of fines, gravels, and some cobbles~~,~~ deposited upstream of the stump (Figure 10).

Figure 10: Typical gravels upstream of stump

Downstream of the stump, the substrate is composed primarily of fines and organic material. The UNT channel is more defined ~~channel~~ than the upper reach of Harlow Creek. Both left and right banks are approximately 3 feet in height and the floodplains appear inaccessible (Figure 11). As the UNT approaches the confluence with Harlow Creek, flow ~~goes through a narrow pinch point. LWM and a second stump are present at this pinch point~~follows the undulating bed surface under and around LWM and a large stump.

Figure 11: Typical UNT channel view with approximately 3 foot high banks

3. Mainstem Harlow Creek from Confluence to – Culvert Inlet ~~to Confluence~~

At the approximate location where the UNT and Harlow Creek meet, an island is present in the middle of the Harlow Creek channel. Trees grow out of the island in the middle. Small gravels and a few cobbles are present ~~as the substrate material~~ on either side of the island. There is a multitude of wood in the channel, all indicative of ~~past~~ historical logging activities (Figure 12). Both banks are ~~about~~ approximately 3 to -4 feet in height and are near vertical, and the channel substrate is ~~all~~ dominated by the presence of fines.

Figure 12: Abundant LWM suggesting historical logging activities

Where the flow converges on the downstream side of the island, there is a large log jam consisting of logs associated with historic timber harvest. Downstream of the jam, the channel narrows to approximately 1~~5~~0 feet wide. The substrate in this area is mostly fines with some gravels and cobbles. Sedge and brush grow in and over the channel in this reach. The bank slopes are gradual and about 2 feet tall~~,~~ and are ~~made~~composed primarily of silt and fines~~soft~~ material. Stands of young trees grow on the banks. The banks are undercut, and the floodplains are flat and accessible (Figure 13 and Figure 14). ~~Natural ~~L~~l~~ogs help form and shore up the banks periodically.

Figure 13: Stream conditions downstream of confluence

Figure 14: Floodplains downstream of confluence

F~~u~~arther downstream, t~~The channel reaches a large, flat, bowl-like pool~~There is a pool~~,~~ approximately 30 to ~~-~~40~~'~~ feet in diameter (Figure 15). LWM from logging activities is present in the pool and racked up at the ~~exit~~ downstream end ~~of the pool~~ towards the right bank (Figure 16). This wood appears to be stable and somewhat decomposed, with no evidence of recent movement. The substrate of the pool is entirely fines, and the floodplains are accessible to ~~the pool~~streamflow.

Figure 15: Large undefined bowl

Figure 16: LWM accumulation near exit of pool

Downstream of~~Past~~ the ~~logging wood~~LWM at the exit of the pool, there is a large deposit of gravels and cobbles (Figure 17). The largest bed material found in this location was 4.5 inches in diameter.

Figure 17: Substrate downstream of LWM near exit of pool

The substrate from this section downstream to ~~deposit up until~~ the culvert inlet is primarily gravels. ~~From this spot to the culvert a~~Approximately 50 feet upstream of the culvert inlet~~away~~, LWM recruited naturally from the banks is present in the channel ~~and lying across bankfull~~and forming accumulations that span the channel between both banks (Figure 18). Valley occlusion has led to some areas where logs are quite dense and accumulating soils, supporting tree and shrub growth, which the stream flows and pools beneath. The area is characterized by a complex of multiple flow paths and sloughs.

Figure 18: Stream conditions between LWM and inlet

The channel shape in this area consists of short vertical banks that slope up towards a flat floodplain. The banks are undercut in the proximity of the culvert and confine the channel in a straight, entrenched planform (Figure 19). Flow contraction due to an undersized culvert is likely driving localized channel bed and bank erosion at the existing inlet. ~~Natural~~Naturally recruited logs ~~shore up the banks~~provide a degree of bank stability in the ~~stretch~~ area~~reach~~ between the racked-up~~logging~~ wood and the culvert. On the right bank near the culvert, a small side channel enters the ~~channel~~stream. It likely carries floodplain flow from upstream to this location. There is LWM present in the side channel.

Figure 19: ~~Incision~~ Bank erosion near culvert inlet

The culvert itself is a ~~4 foot wide~~4-foot-wide CMP mitered to slope (Figure 20). The culvert inlet is perched approximately 4 inches above the channel bed.

Figure 20: Culvert inlet

The planform in the upstream segment~~reach~~ of MP 142.48 overall is characterized by a meandering channel with a slope of approximately 1 to ~~-~~2 percent outside of culvert backwater influence. ~~in combination with~~ The segment also has defined banks interspersed with accumulations of LWM from both past logging influences and natural recruitment that cause occasional pools and gravel deposits to form.

Downstream ~~Reach~~

At the outlet of the culvert, there is an approximate ~~water level drops approximately~~ 6-inch~~es~~ drop from the culvert apron~~propn on~~ below to rip~~-~~rap which lines the channel bed (Figure 21). The existing metal apron is failing due to corrosion and past undermining at the transition to the channel. ~~-~~Rip~~-~~rap is present in the channel for 15 feet downstream of the culvert.

Figure 21: Culvert outlet

The right bank is about 3 to ~~-~~4 feet tall, while the left bank is lower with an accessible inset floodplain surface. Stands of young trees and ferns grow on the banks. Some undercutting of the channel bank is present at a bend downstream of the rip rap. Small debris and brush ~~is~~ are racked up after this bend,~~;~~ throughout the whole of the downstream reach.~~,~~ ~~a~~All ~~LWM~~ debris ~~observed~~ within the channel appears to be a result of natural recruitment ~~along the banks and was not indicative of logging presence~~, though the pieces and accumulations are not stable enough to provide a lasting influence on channel form or processes (Figure 22).

Figure 22: Brush and debris in channel

The reference reach begins downstream of the racked LWM roughly 45 feet downstream from the culvert outlet.~~Downstream of the LWM racking, the reference reach begins~~ (Figure 23). The left bank is ~~slightly lower than the right,~~ about 1 to -2 feet tall ~~while~~ and the right bank is about 2 to -3 feet tall. The left bank floodplain is flat before sloping up to the roadway. The right floodplain is moderately sloped. Roots of trees form the banks periodically on both ~~banks~~sides of the channel. The channel itself is 4 to 5 feet wide, ~~and flat, with no clear thalweg~~and entrenched within its near vertical banks, owing to the influence of the undersized culvert opening. This channelized section is armored and relatively stable, as evidenced by the establishment of moss on top of streambed cobbles.

Figure 23: Reference reach

All three ~~bankfull widths~~BFWs were taken through this section of stream. BFW~~ankfull width~~ measurements and photographs are provided in Section 2.8.2. The channel substrate is gravels and cobbles, and a pebble count was performed here as well (Figure 24 and -Figure 25~~Figure 25~~). Trees are present on the banks and in the floodplains, but there is little brush. The reference reach selected is most likely influenced by the culvert discharge, but a superior reference reach was not found due to the incised channel banks throughout the channel both upstream and downstream.

Figure 24: Reference reach substrate and pebble count location

Figure 25: Reference reach substrate (gravelometer for scale)

Downstream of the reference reach, the channel shape changes to become narrower and deeper with inaccessible floodplains (Figure 26). Both banks are 3 to ~~-~~4 feet in height and show signs of erosion due to channel incision (Figure 27). The banks are vegetated with brush and trees, and the substrate is gravels and cobbles.

Figure 26: Typical channel conditions downstream of reference reach

~~Both banks are 3-4 feet in height and show signs of erosion due to channel incision (Figure 27). The banks are vegetated with brush and trees, and the substrate is gravels and cobbles.~~

Figure 27: Channel incising and undercut bank

Approximately 30 feet before the end of the survey extents, there is a ~~6 inch~~6-inch water level drop over sedges and sediment present in the channel (Figure 28). At the very downstream end of the survey, the channel changes shape again, widening and aggrading with limited connections to a small wetland complex off the right bank. The wetland complex includes areas of ponded water, multiple main channel connections, and stands of emergent wetland vegetation such as *Carex spp*. ~~to become wetland-like. Sedges are present in the channel.~~

Figure 28: WS drop over sedge

The planform in the downstream reach of MP 142.48 overall is characterized by plane-bed morphology. The channel itself is flat without a defined thalweg, and the slope is approximately 2 percent.

2.7.2 Fish Habitat Character and Quality

Upstream of the US 101 crossing, Harlow Creek and its left bank UNT flow through a mature mixed forest consisting of alder (*Alnus rubra*), Western hemlock (*Tsuga heterophylla*), Douglas fir (*Pseudotsuga menziesii*), and western red cedars (*Thuja plicata*). There is a dense shrub understory with native species including evergreen huckleberry (*Vaccinium ovatum*), salmonberry (*Rubus spectabilis*), willows (*Salix* spp.), vine maple (*Acer circinatum*), salal (*Gaultheria shallon*), and sedges and ferns. The shrub understory is particularly dense at the upstream end of the surveyed reach where the mature tree canopy recedes back from the stream channel creating an open canopy. Downstream of the small island, the mature tree canopy covers and shades the stream, and the understory shrubs become much less dense. The mature forest and shrub cover provides good shading, nutrient inputs, and potential for LWM recruitment. LWM is important in western Washington streams in that it provides cover for fish and contributes to stream complexity, which is beneficial to salmonids.

There were many places where large logs and woody material were present within the stream channel and banks, and LWM was abundant throughout the upstream reach. There were over 50 significant pieces of LWM in the channel and on the banks, with several locations of log piles. These logs generally ranged in size from 8 to 36 inches in diameter and also included some root-wads. Much of this wood was perched above the wetted channel and not interacting with streamflow under low flow conditions.

There is a large LWM ~~pile~~ accumulation that covers the stream channel near the downstream end of the reach. ~~The abundant LWM and debris wracking can pose potential temporary passage barriers to fish moving upstream or downstream particularly during low flow periods. Returning coho often gather at the mouths of streams and wait for the water flow to rise, such as after a rain storm, before heading upstream. The higher flows and deeper water enable the fish to pass obstacles, such as logs across the stream or beaver dams that would otherwise be impassable.~~ The abundant LWM provides ~~good~~ cover, velocity refuge, ~~-~~ and habitat complexity for fish throughout the upstream reach. ~~during higher flows.~~.

Generally, the upstream channel can be characterized by a complex of pools and small sloughs forced by riparian vegetation, LWM, and rootwads. Pools, and the transition areas between pools and riffles, are important habitat for adult and juvenile salmon, allowing them to rest and feed. The slow water of pools also allows the fish to rest and feed on invertebrates that accumulate there~~,~~ ~~and~~while the depth provides protection from predators~~,~~ as well as cooler water. Further upstream, t~~T~~he stream is ~~more small~~ ~~narrow~~narrower and shallower, and instream habitat is comprised predominantly of shallow glides and riffles with a few small pools associated with LWM. The water was colored dark brown with abundant tannins~~, but does not pose a water quality issue for salmon use~~. Fish in western Washington often utilize waters that are ~~tanic~~tannic and are successful in rearing, growth, and reproduction in these areas.

The abundant LWM provides habitat complexity and cover for salmonids using this reach for rearing and migration, particularly during high flow periods; however,~~.~~ ~~T~~these functions are limited during summer low flows such as during the field visit where shallow water, ~~and~~ LWM jams and pool isolation may impede juvenile fish movement through this reach. Spawning gravels are limited and the upstream reach does not provide much suitable salmon spawning habitat and will therefore primarily provide rearing opportunity for juvenile salmonids.

The downstream reach parallels the highway for the length of the field survey and the riparian corridor consists of a relatively narrow strip of mixed forest including western hemlock, Douglas fir, and alders. The right bank is located next to a large timber harvested area that has been replanted with young conifers, and the riparian corridor of mature trees is also restricted to a narrow strip. Although the mature tree cover along both banks provides good shading for the stream, the constricted riparian corridor limits potential LWM recruitment. LWM is much less abundant in the downstream reach than upstream. There were no pieces of significant LWM within the wetted channel except a 10-inch diameter conifer log across the top of bankfull about mid-reach. There was an area just downstream of the culvert that had many large branches and other smaller woody material in and across the channel. The shrub understory is abundant along both banks and consists of native species including vine maple, salmonberry, and willows.

The downstream channel is generally straight and lacks habitat complexity. It is predominantly riffle and glide habitat over small cobbles and fines, with very few pools or cover from LWM. A small scour pool along an undercut bank provides the only in-stream pool habitat in the downstream reach~~.~~ However, a small complex of wetlands including ponded water and emergent wetland vegetation exists off the right bank with minimal connection to the main channel. This could serve as important water storage and overwintering refuge for migrating fish. In some areas, s~~S~~edges and aquatic vegetation have grown within the stream channel and were visible during the late-June field visit expressing low flow conditions. ~~and t~~The substrate is dominated by fines at the downstream end of the surveyed reach. Suitable spawning habitat for the salmonids that inhabit the stream is lacking in the downstream reach. This reach is primarily suited to be a migratory corridor, particularly during periods of higher flows. Some limited rearing habitat is present, but the lack of connection with the adjacent wetlands as well as pools and habitat complexity reduce this function as fish do not have adequate resting areas or ~~adequate~~ cover.

2.8 Geomorphology

Geomorphologic information provided for this site includes selection of a reference reach, the basic geometry and cross sections of the channel, stability of the channel both vertically and laterally, and various habitat features.

2.8.1 Reference Reach Selection

A section of stream approximately 45 feet downstream of the culvert (Figure 29~~Figures 29~~ and 30) was chosen as the reference reach~~,~~ because ~~it is most representative of a naturally occurring streambed, with~~it has the least amount of anthropogenic influences within the surveyed limits. This reach has an approximate average channel gradient of 1.5 percent. A pebble count was conducted at the reference reach. ~~Figure 30 shows the location of the reference reach.~~ This reference reach was used primarily for proposed design channel shape and comparison to proposed hydraulic results throughout this Preliminary Hydraulic Design (PHD) Report, as the entire upstream reach was influenced by ~~copious~~ an unnatural ~~amounts~~ density of LWM from historic logging activities. While the reference reach is not completely outside of the area of influence from the existing culvert and road prism, and shows signs of degradation, its selection is acceptable for BFW measurement and channel design~~-~~.

Figure 29: Typical segment of ~~R~~reference reach ~~looking downstream~~on June 25, 2021. Flow direction is from right to left of photo.

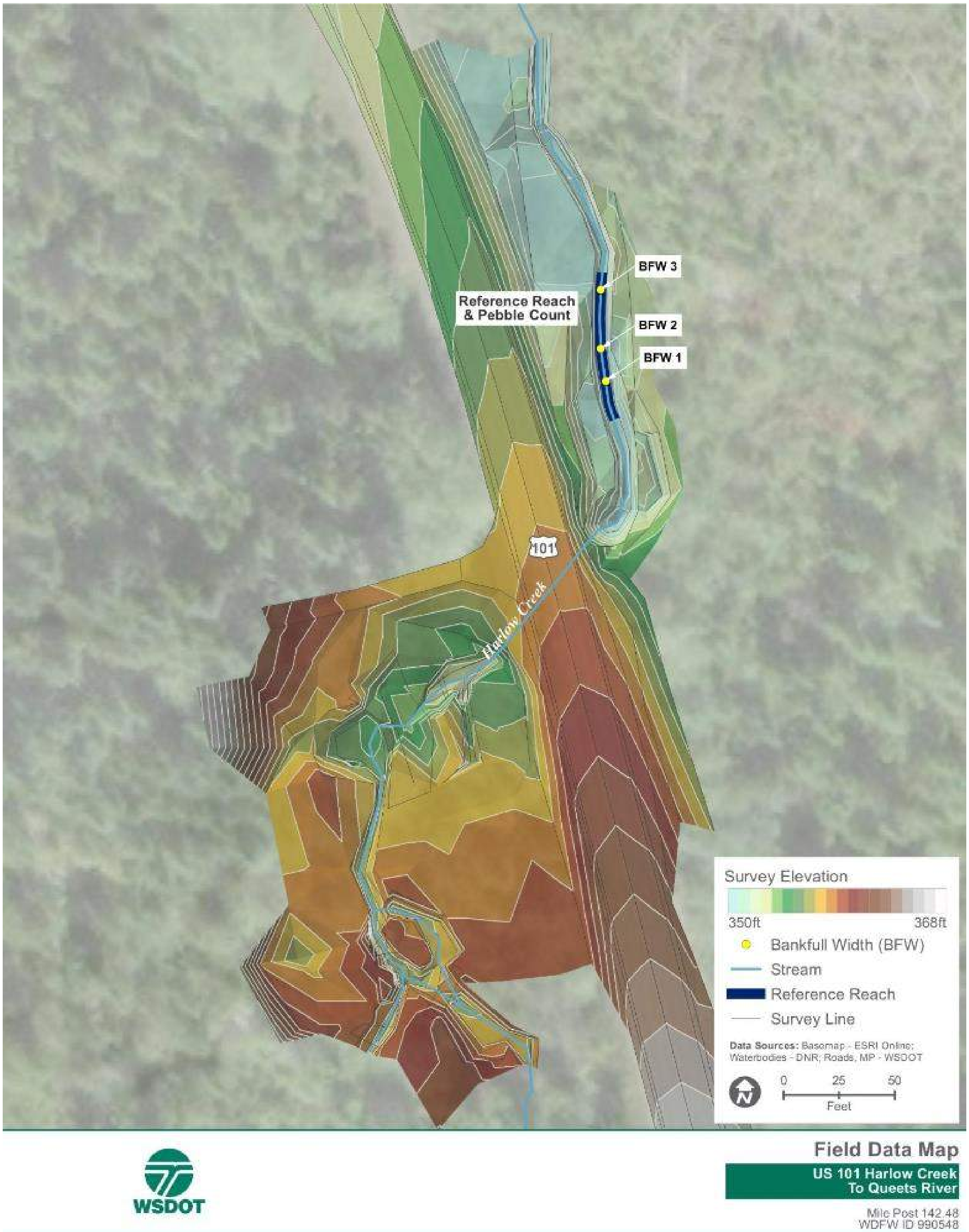


Figure 30: Reference reach

2.8.2 Channel Geometry

Channel planform at this crossing is characterized by a meandering and undefined channel upstream with a much straighter and entrenched channel downstream. Upstream, two tributaries converge into ~~one~~ a reach where~~channel before~~ flow is significantly influenced by the presence of ~~restricted by a narrow channel with~~ several log jams and spreads ~~into the~~onto an accessible floodplain at high flow events. The slope is approximately 2.2 percent (see Section 2.8.4). Downstream, the channel takes a sharp bend following the culvert outlet and flows parallel ~~to~~ with the road prism ~~until the downstream survey extents~~within a single-threaded, plane-bed channel. The slope is approximately 1 to 2 percent. The reference reach is located from approximately STA 1+05 to STA 1+90. The cross-section geometry through ~~this~~ the reference reach ~~will~~ is ~~be~~ used for design comparison, and the upstream longitudinal profile slope of 2.2 percent (Section 2.8.4) ~~will~~ is ~~be~~ used for the slope ratio design comparison.

Figure 31~~Figure 31~~ shows typical detailed cross sections at the project site developed from the WSDOT survey: one upstream of the U.S. 101 crossing, one just upstream of the culvert, and one downstream of the culvert. The upstream-most cross section shown (STA 4+16) is narrow, with a wide, flat floodplain that is often wetted due to the abundance of LWM ~~forcing~~ spreading flow out of the channel. The cross section ~~just~~ immediately upstream of the culvert (STA 3+18) ~~is~~ includes a large scour pool in front of the culvert as all flow ~~rejoins~~ converges at the ~~channel~~culvert inlet approach. The downstream-most cross section shown (STA 1+56, in the reference reach) has the widest channel shape with a defined thalweg and terraced floodplains. ~~From this figure, it is clear that t~~The channel geometry within the reference reach (STA 1+56) provides the best-available reference cross section for the design of the proposed crossing to provide adequate depth at low-flows and an accessible floodplain surface near channel-forming flows.

The width-to-depth ratio is measured at the reference reach cross section at STA 1+56 and is approximately 6:1. The channel averages 1 to 1.5 feet deep. The channel evolution stage was evaluated in the reference reaches and estimated to be in Stage I of the Channel Evolution Model (Schumm et al. 1984).

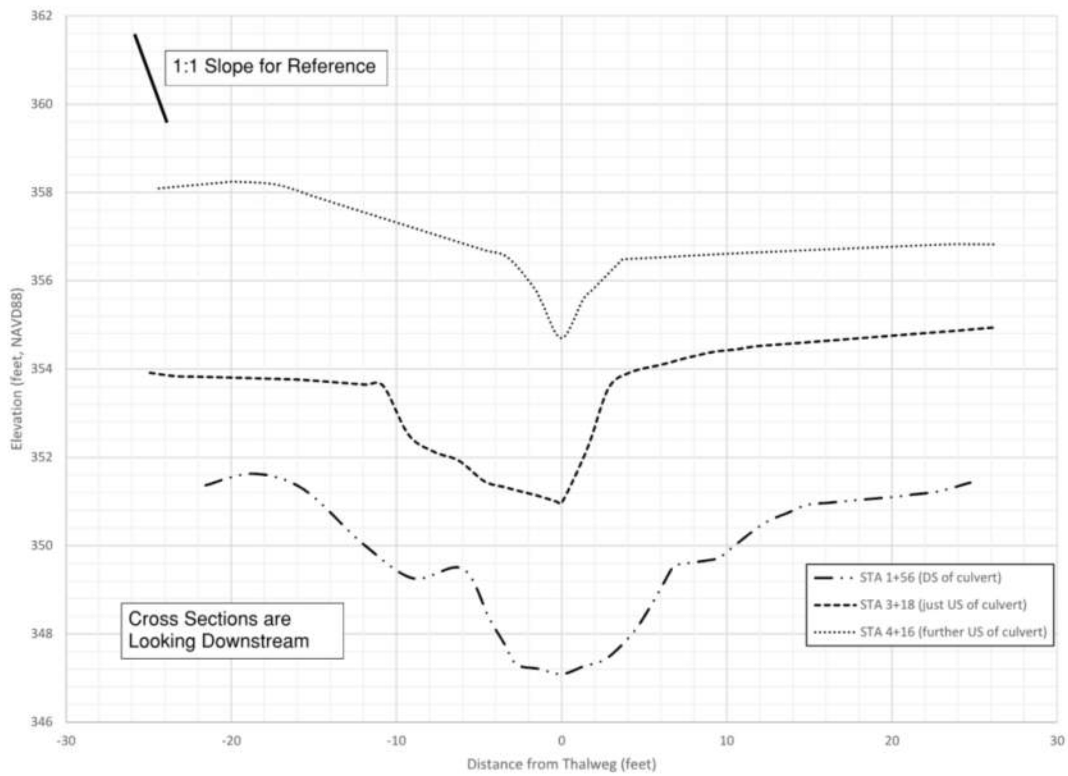


Figure 31: Existing cross-section examples

~~Because no site visit could be performed at the time of the initial writing of this report, three~~Initial estimates of BFW~~s~~ were ~~originally estimated~~ derived ~~using~~ from ~~several~~ two methods. First, using the existing-conditions model in SMS (described below in section 4), the 2-year flow top width was ~~measured~~ computed at ~~several~~ three locations. ~~Second, a~~At these same locations, the top of bank width was also measured based on the topographic survey provided by WSDOT (Figure 32, and listed in Table 3). ~~The locations where these three BFWs were measured are identified in Figure 32, and listed in Table 3.~~ BFW 2~~B~~ is located in the identified reference reach and BFW 1~~C~~ is ~~just~~ immediately upstream; the detailed BFW cross sections ~~can be found~~are shown in Figure 32~~Figure 32~~.

~~The measurements at these three locations were averaged.~~ The average 2-year top width (modeled) ~~was~~ is 10.9 feet, while the average top of bank width (surveyed) ~~was~~ is 9.6 feet. The average of these two ~~measurements~~ values results in an initial ~~estimated~~ BFW estimate of 10.3 feet.

For comparison, a BFW was calculated based on the WCDG (Barnard et al. 2013) regression equation for high-gradient, coarse-bedded streams in western Washington. Using the basin area (0.31 square mile) and average mean annual precipitation (116.8 inches [in]/year) the regression equation estimates a BFW of 10.3 feet, the same value as the initial estimated BFW. The WCDG regression equation method BFW was not used to determine a design BFW~~,~~ but is provided for informational purposes and for comparison. ~~The initial estimated BFW of 10.3 feet is equal to the WCDG regression equation result of 10.3 feet, so this measurement was used as the design BFW.~~

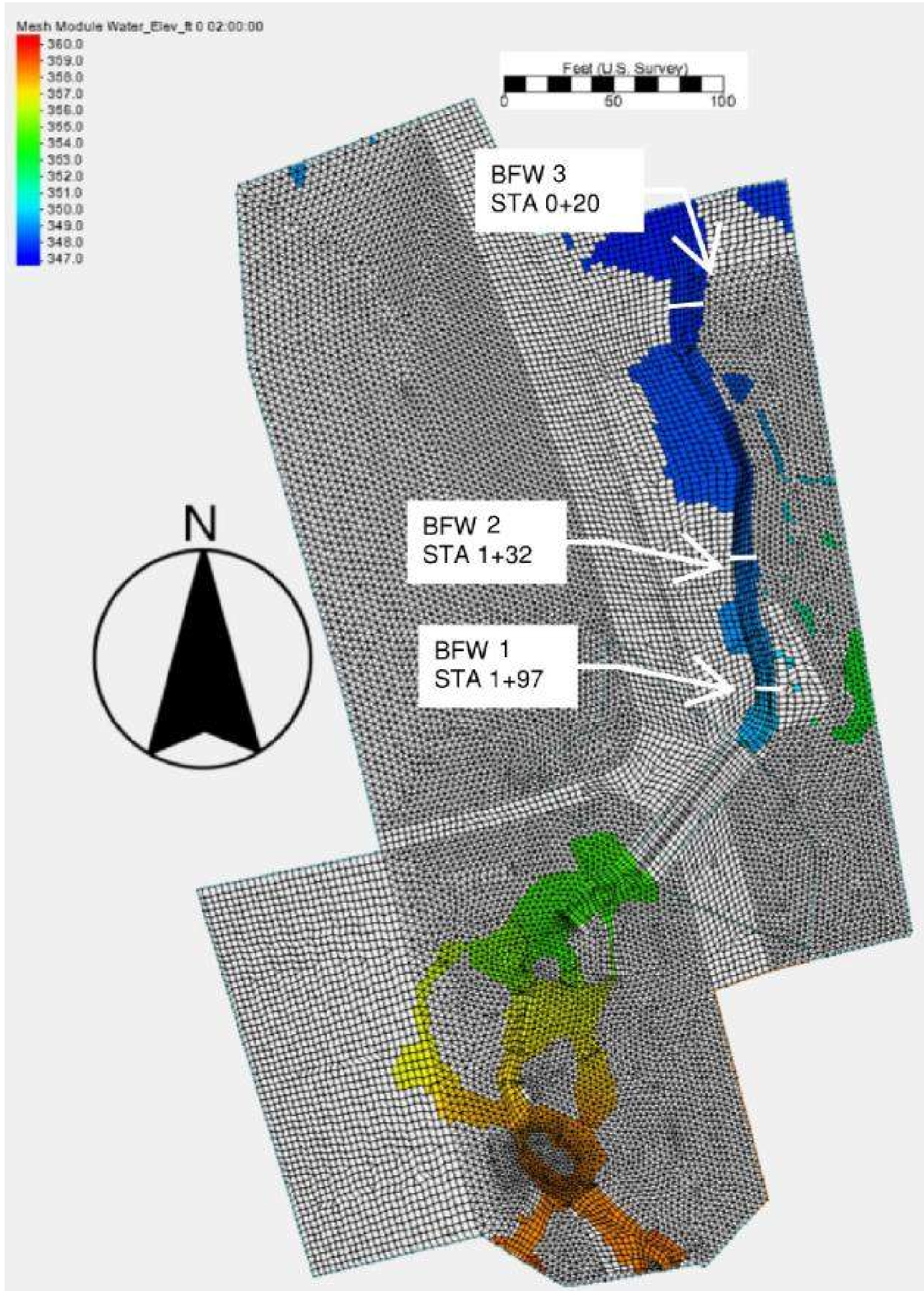


Figure 32: Location of bankfull width measurements

Table 3: Bankfull width ~~measurements~~ estimates from hydraulic model and WSDOT topographic survey

BFW #	2-Year Top Width from Model (ft)	Top of Banks Width from Survey (ft)	Included in Design Average	Concurrence Notes
1 (STA 1+97)	9.2	10.7	Yes	WDFW and Tribe concur ~~No stakeholder meeting held~~
2 (STA 1+32)	8.5	9.3	Yes	WDFW and Tribe concur~~No stakeholder meeting held~~
~~A~~3 (STA 0+20)	14.9	10.2	Yes	WDFW and Tribe concur ~~No stakeholder meeting held~~
~~B (STA 1+32)~~	~~8.5~~	~~9.3~~	~~Yes~~	~~No stakeholder meeting held~~
~~C (STA 1+97)~~	~~9.2~~	~~10.7~~	~~Yes~~	~~No stakeholder meeting held~~
Design average	10.9	9.6		
Overall design average	**10.3**			

~~Once a~~During the first site visit conducted~~was performed~~ on July 28th, 2020 three initial BFW measurements were taken in the field downstream of the crossing ~~to avoid the influence of LWM~~in the reference reach, see Table 4~~Table 4~~. The ~~BFWs~~ measurements ranged from 7.4 to 7.9 feet, resulting in an average width of 7.6 feet. See Appendix B for bankfull width measurement photos. ~~Figure 33, Figure 34, and Figure 35 show the stream conditions where all three BFWs were measured measurements were taken, and~~ Figure 30~~Figure 30~~ shows the ~~overall location where these BFWs were measured~~location of the respective three measurements.

~~A secondary site visit with HDR, WSDOT, WDFW, and the tribes has not yet been conducted to gain concurrence on BFWs and other design considerations because of COVID-19. Table 4 summarizes BFW measurements taken during the July 28th site visit, which resulted in an average BFW of 7.6 feet.~~

Table 4: Bankfull width measurements from first site visit on July 28, 2020

BFW #	Width (ft)	Included in design average
1	7.9	~~Yes~~No
2	7.4	~~Yes~~No
3	7.5	~~Yes~~No
~~Design a~~Average	7.6	

~~The average site visit measured BFW of 7.6 feet is smaller than the previously estimated BFW of 10.3 feet. This is likely because in the original estimate, the 2-year top widths were used as a factor; those~~

~~values were much larger than the other measurements taken in the field and using survey data because of the conservative hydrology modeled in the basin.~~

~~To be conservative, it was decided to size the proposed structure based on the original estimated BFW of 10.3 feet instead of the smaller measured 7.6 feet.~~

A second site visit was conducted on June 25, 2021 to independently evaluate the BFW. Field measurements were taken at previously occupied transects in the reference reach according to vegetation, surface sediment, and topographical features. BFW measurements from the second site visit are shown in Figure 33~~Figures 36~~, Figure 34~~Figure 37~~, and Figure 35~~Figure 38~~ which reoccupy BFW sites 1, 2, and 3 from the first site visit, respectively.

Figure 33: BFW 1 from the second site visit on June 25, 2021

Figure 34: BFW 2 from the second site visit on June 25, 2021

Figure 35: BFW 3 from the second site visit on June 25, 2021

A summary of BFW measurements from the second site visit listed in Table 5~~Table 5~~, which were taken at the same locations as the first site visit. The difference in measurements is attributed to inclusion of inset floodplain surfaces connected to the left bank at channel forming flows during the second site visit.

Inundation of these accessible benches are typical for low-to-moderate grade streams with sinuous planforms and broad floodplains, such has Harlow Creek.

Table 5: Bankfull width measurements from second site visit on June 25, 2021

BFW #	Width (ft)	Included in design average	Concurrence notes
1	11.0	Yes	WDFW and Tribe concur ~~Tribe concurrence~~
2	11.25	Yes	WDFW and Tribe concur~~Tribe concurrence~~
3	9.0	Yes	WDFW and Tribe concur~~Tribe concurrence~~
~~Design~~ Average	**10.4**		**~~WDFW and Tribe concur~~**

The average BFW from the second site visit is 10.4 feet, which validates the initial BFW estimate of 10.3 feet. WDFW and the Tribe performed individual site visits to measure BFWs and a concurrence meeting was held virtually on August 9, 2021 to agree on a design ~~measurement. The QIN (Tribe) gave concurrence on the proposed BFW of 10.3 feet on October 2, 2020 and matches with the climate-predicted BFW recommended by WDFW. Therefore, the proposed design~~ BFW ~~is~~of 10.3 feet.

2.8.3 Sediment

One pebble count was taken during the July 2020 site visit, approximately 45 feet downstream of the crossing within the reference reach with 300 particles. Two pebble counts of 100 particles each were taken during the June 2021 site visit, one upstream and downstream of the crossing. The upstream pebble count was taken approximately 120 feet upstream of the culvert inlet and the downstream pebble count occupied the 2020 pebble count location. ~~During the July 28, 2020 site visit, a Wolman pebble count was conducted downstream of the U.S. 101 culvert crossing in an area beyond the influence of the culvert, approximately 45 feet downstream of the culvert inlet and in the reference reach. See Figure 30 above for the pebble count location. Only one pebble count was conducted, but this single pebble count consisted of just over 300 pebbles, which is considered adequate.~~

The results of the pebble count indicated that the bed material was composed primarily of fine and medium to coarse gravels and small cobbles. ~~While counting, it was apparent from both the measurements and visual inspection that sediment throughout the surveyed reach consists of a variety of sand, gravels, and cobbles.~~ The cumulative distribution and pebble sediment sizes for the upstream pebble count is provided in Table 6 and Figure 36. A photo of the downstream substrate is provided in Figure 37~~Figure 39Figure 36~~ with a gravelometer for reference. Table 7~~Table 7Table 5~~ and Figure 38~~Figure 40~~ provides a summary of downstream pebble count data. ~~The results of the pebble count indicated that the bed material was composed primarily of medium to coarse gravels and small cobbles.~~ The largest sediment size in th~~is~~e downstream reach observed was 10.1 inches (0.8 foot) in diameter. ~~See Figure 37 for the sediment size distribution observed on site.~~ Pebble count locations were

~~reoccupied on the June 25, 2021 site visit, and sediment distributions were verified by repeat pebble counts.~~

Table 6: Upstream sediment properties from 2021 pebble count

Particle	Upstream Diameter (in)	Upstream Diameter (mm)
D_{16}	0.1	2.5
D_{50}	0.1	3.6
D_{84}	0.3	8.4
D_{95}	0.8	21.0
D_{100}	1.3	33.0

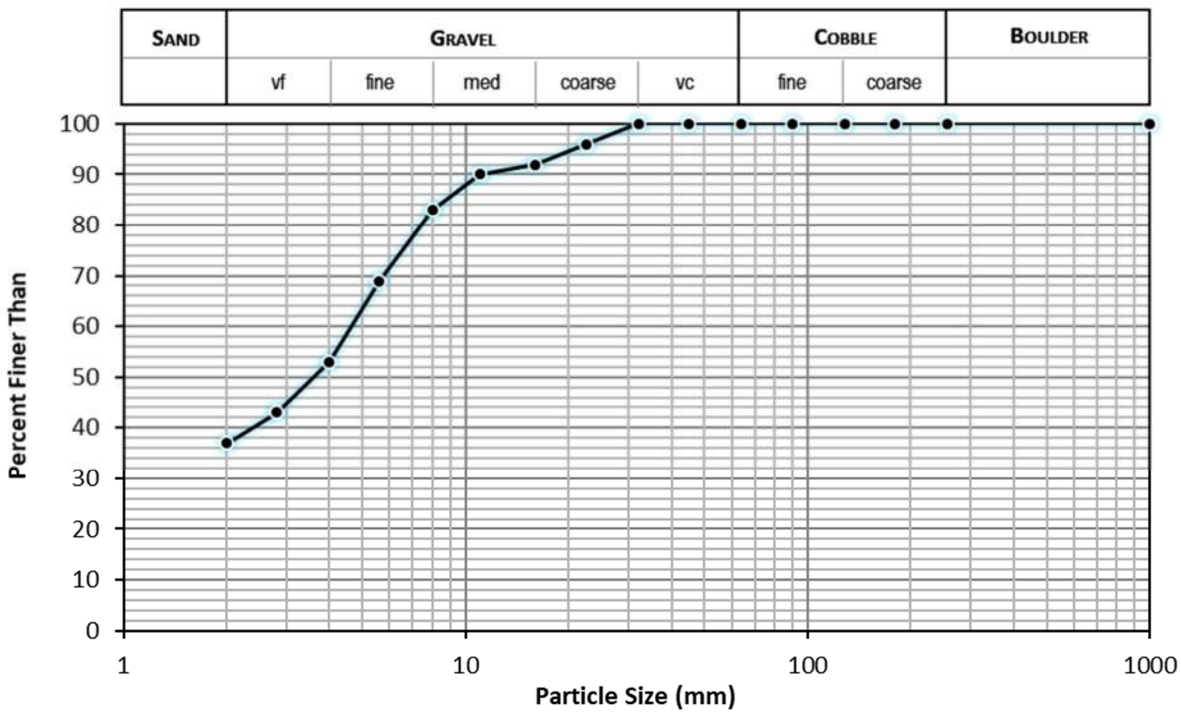


Figure 36: Upstream sediment distribution from 2021 pebble count

Figure 37: Downstream ~~S~~substrate with gravelometer for reference from first site visit on July 28, 2020

Table 7: Downstream s~~S~~ediment properties ~~of project crossing from first site visit on July 28, 2020~~

	2020 Count		2021 Count	
Sediment Size	Diameter (in)	Diameter (mm)	Diameter (in)	Diameter (mm)
$\mathbf{D_{16}}$	0.4	10.2	0.4	10.2
$\mathbf{D_{50}}$	1.3	33.0	1.4	35.6
$\mathbf{D_{84}}$	2.9	73.7	3.0	76.2
$\mathbf{D_{95}}$	4.0	101.6	4.8	121.9
$\mathbf{D_{100}}$	10.1	256.5	7.1	180.3

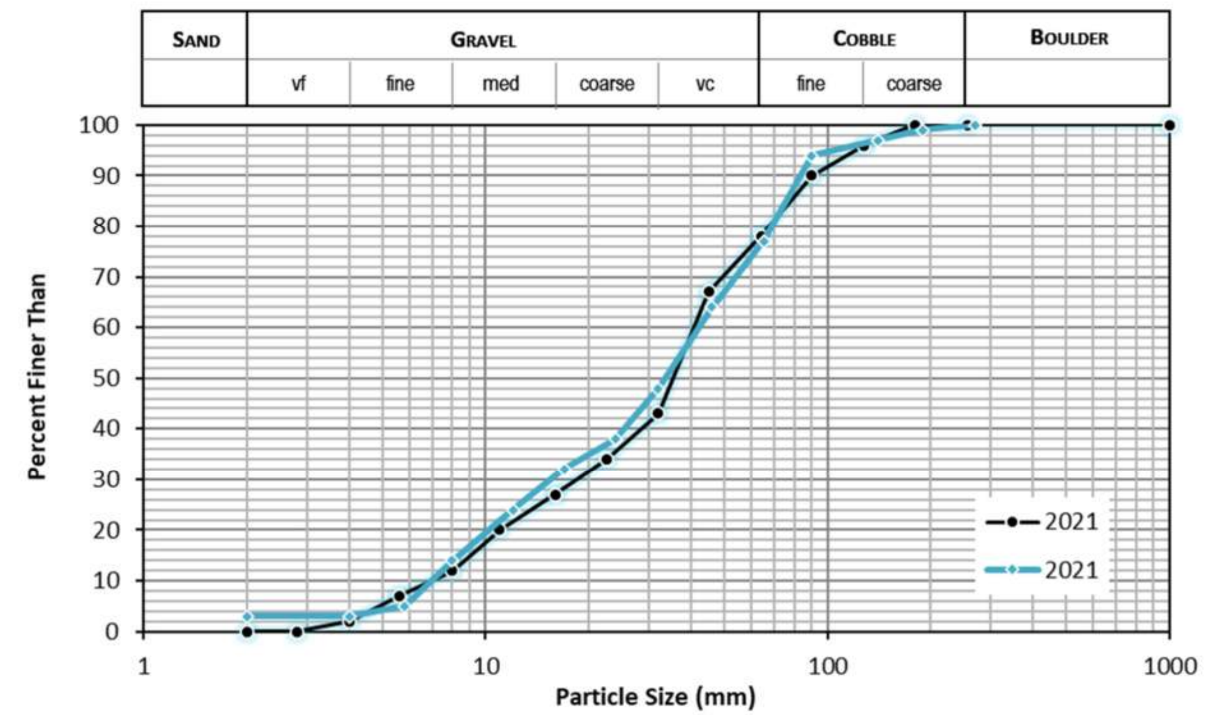


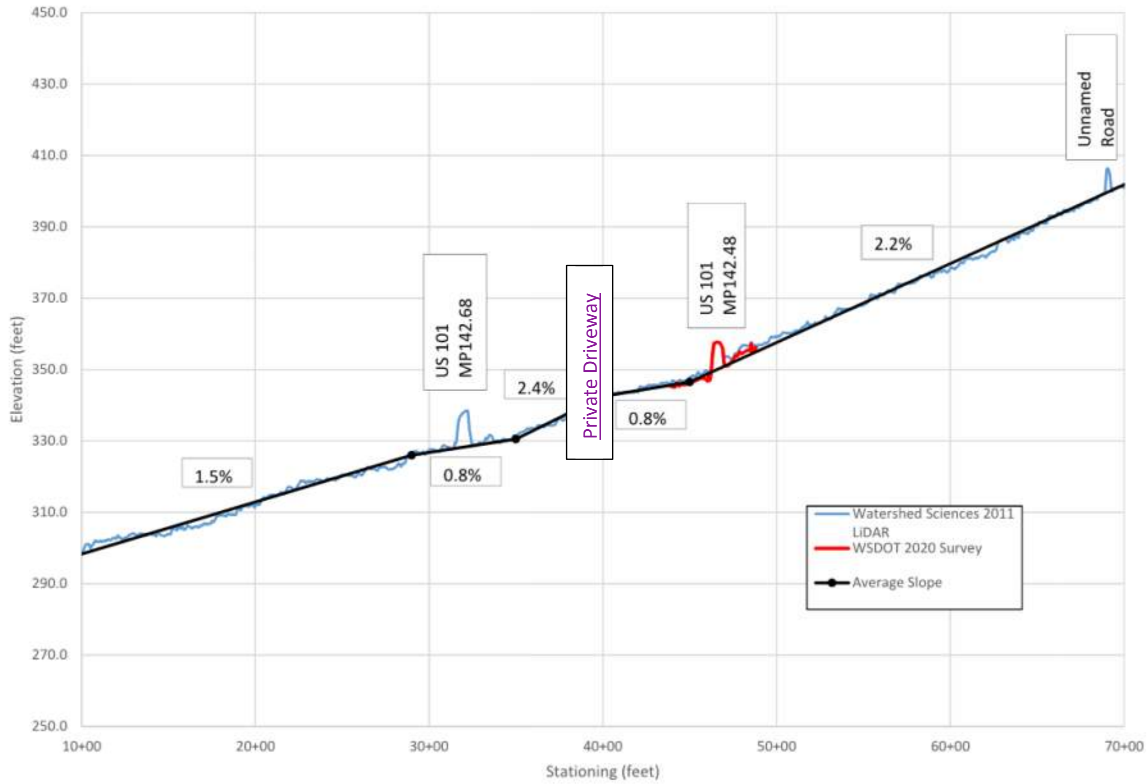
Figure 38: Downstream ~~S~~sediment size distribution ~~from first site visit on July 28, 2020~~

2.8.4 Vertical Channel Stability

A long channel profile was developed from 2020 WSDOT survey data and 2011 light detecting and ranging (LiDAR) data (Watershed Sciences 2011). Both ~~of these~~ data sets show the road embankment at the crossing locations. The channel profile (Figure 39~~Figure 41Figure 38~~) describes ~~slopes~~ the channel bed approximately 2,000 feet upstream and 3,000 feet downstream from the project culvert and includes major landmarks along the tributary. Upstream of the survey extents and almost all the way through the survey, the slope is approximately 2.2 percent. Downstream of the survey, the slope ~~changes to approximately 0.8 percent for about 500 feet and then steepens to approximately 2.4 percent for about another 500 feet~~averages approximately 1.5 percent. There is a private driveway crossing in this reach that appears as a bump on the LiDAR profile and may affect the stream slope. ~~At this point~~Below this, the tributary travels through the culvert at MP 142.68 (the next downstream WSDOT crossing) at an approximate slope of 0.8 percent for 500 feet. Farther downstream, the slope stays at approximately 1.5 percent for approximately 2,000 feet. The slopes and channel geometries within the survey extents are described in more detail in the paragraphs below.

The upstream channel is unconfined and undeveloped. The channel is characterized by the presence of several stable log jams captured in the survey. As a result, pools have formed, and flow ~~has~~ spreads out into the floodplains throughout the upstream reach at ~~all~~ presumably most high flow events. Additionally, the log jams have been decelerating the approach velocity of the flow~~,~~ and limiting degradation in the upstream reach. Starting at the upstream extents of the survey approximately 200 feet upstream of the culvert inlet, the channel has a slope of approximately 1.1 percent for approximately 50 feet and is made up of two separate tributaries that ~~join together about~~meet nearly 140 feet upstream of the culvert inlet. ~~After~~ Approximately 50 feet below the confluence, the channel steepens to approximately 5 percent and continues until it reaches the upstream culvert inlet. There is potential for ~~degradation~~ erosion at the upstream inlet of the culvert ~~because~~ due to the floodplain flow ~~all enters the~~converging with the main channel ~~again~~ at th~~is point~~e structure opening~~,~~. Conditions ~~creating a~~leading to local contraction scour ~~pool~~are likely to persist ~~with an~~as long as the undersized structure remains but do~~es~~ not pose a long-term or reach-wide risk of vertical channel instability.

Downstream, the channel has both confined and unconfined stretches. ~~It appears that f~~From the culvert outlet to ~~a point~~ approximately 110 feet downstream, the channel is confined and entrenched within defined banks. At this point, the left bank becomes low and terraced and flow spills out into the floodplain, creating an unconfined channel. Throughout the entire downstream reach, the average slope of the surveyed extent is approximately 1 percent ~~until the extents of the survey approximately 250 feet downstream of~~below the culvert outlet. The existing drop at the culvert outlet will be removed, including scour protection rock, in proposed conditions ~~and tie~~by daylighting the channel into the downstream ~~channel~~bed elevations at a constant slope, ~~re is potential for degradation erosion at the culvert outlet because of~~resulting from ~~the drop that occurs from~~at ~~the culvert outlet to the streambed below, though the~~this armored downstream reach is stable. ~~There is little potential for aggradation in the reach. Upstream, s~~Sediment supply, composed ~~is~~ primarily of fines with gravel, is ~~deposits~~ deposited near the existing log jams. Sediment yield potential within the basin ~~is likely to~~may fluctuate with changes to land use and land ~~cover~~cover but does not pose a significant risk of aggradation in the project reach.


Unnamed Road
2.2%
US 101 MP142.48
US 101 MP142.68
Private Driveway
2.4%
0.8%
1.5%
0.8%
Watershed Sciences 2011 LiDAR
WSDOT 2020 Survey
Average Slope
Elevation (feet)
Stationing (feet)

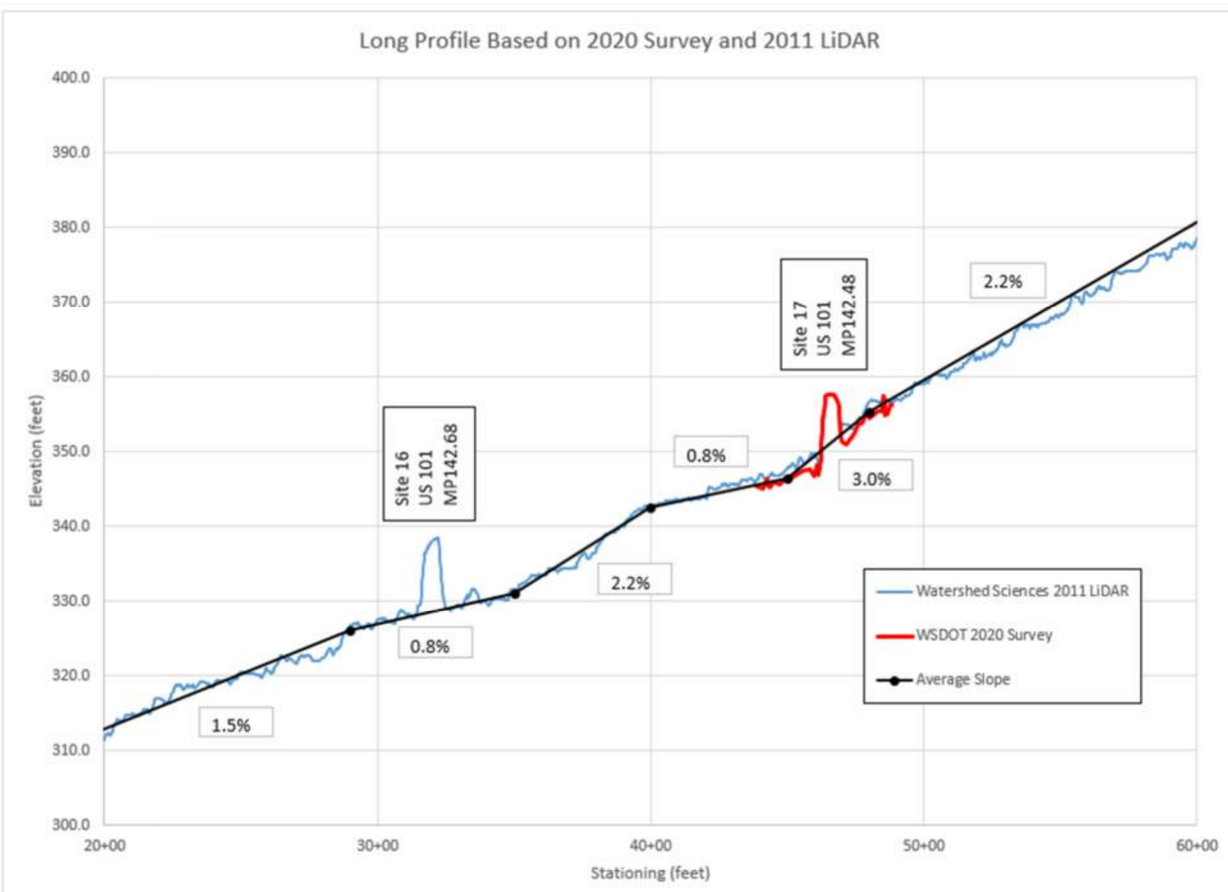

Long Profile Based on 2020 Survey and 2011 LiDAR
Site 17 US 101 MP142.48
2.2%
Site 16 US 101 MP142.68
0.8%
3.0%
2.2%
0.8%
1.5%
Watershed Sciences 2011 LiDAR
WSDOT 2020 Survey
Average Slope
Elevation (feet)
Stationing (feet)

Figure 39: Watershed-scale longitudinal profile with average slopes

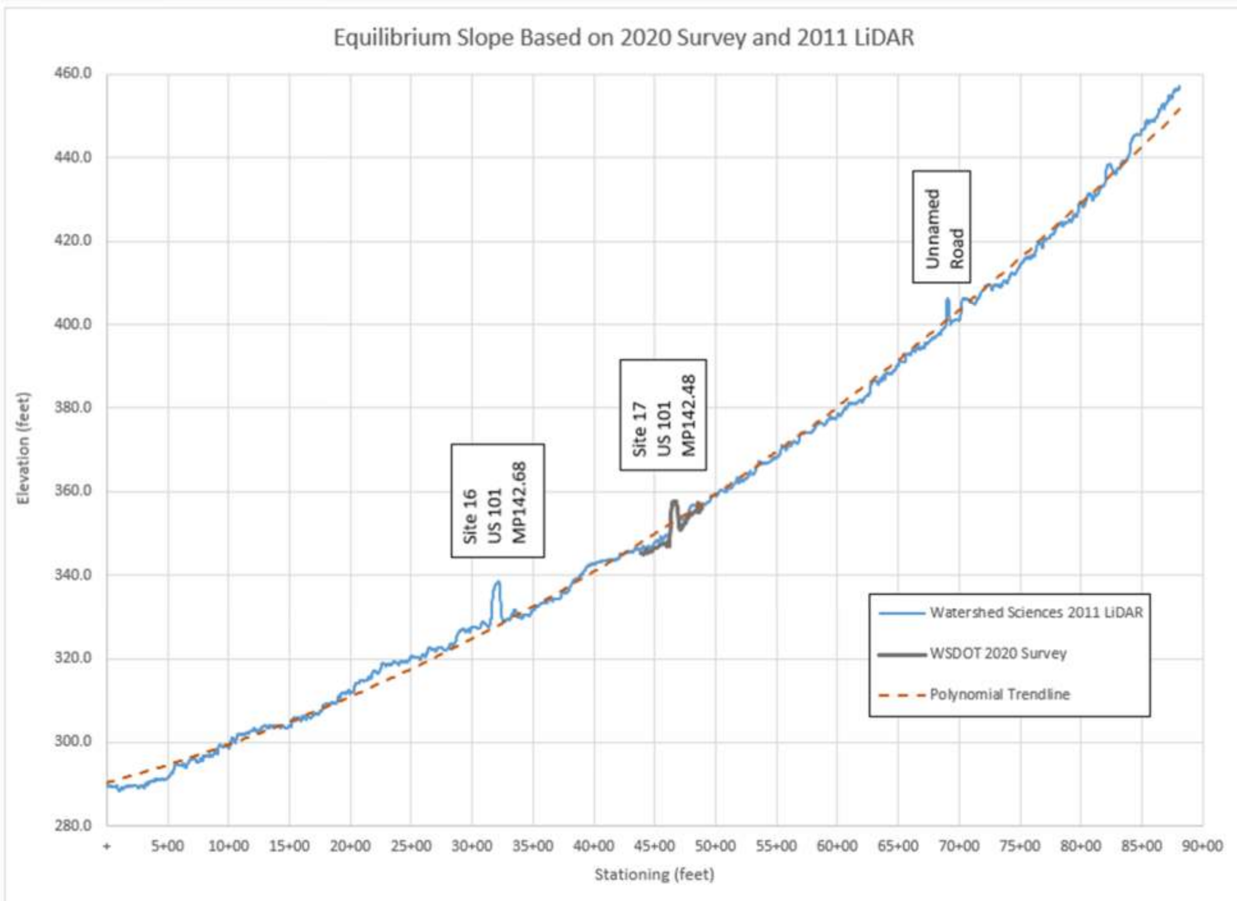


Figure 40: Watershed-scale long profile with polynomial equilibrium slope line

2.8.5 Channel Migration

Channel migration was assessed primarily ~~by~~ through ~~using historical imagery and modeling results~~field observations. The historical aerial imagery ~~gives~~ provides ~~little information~~few insights on channel migration near the project site ~~because the channel is in a forested area, making it difficult to decipher where the channel is in each aerial photo~~due to canopy cover. The upstream-most reach within the survey extents has its channels filled with an abundance of debris and wood from historical logging activities, including a wood accumulation that totals 60 feet in length. There are several accumulations formed by key pieces across the middle of the channel. The cumulative effect of the logjams are split flow paths, creation of broad floodplain surfaces, and deposition of fine sediment. Where wood is not present, a low flow channel is carved from unconsolidated fine sediment.

Significant bank erosion in ~~-~~the upstream reach is present in the approach channel to the culvert inlet, which is likely driven by flow contraction at high flow events. The straightened plane-bed planform of the approach reach is indicative of channel incision from elevated velocities rather than lateral channel migration.

~~Based on modeling results, the channel is unconfined upstream. There is floodplain flow at all flow events upstream which is due to the flow overtopping the banks and, not due to backwater from the culvert. At the 2-year flow event, there are three distinct flow paths: the main channel and two side channels on either side. At higher flows, flow spreads across the entire floodplain and only a few high points in the survey are not submerged. However, all flow rejoins the channel at a pool upstream of the culvert inlet, so even though channel migration may be possible in the upstream reach, it is not anticipated to be a concern through the structure.~~

Downstream, there are terraces ~~that are~~ activated at higher flows, but the channel itself is confined and there is a low risk for channel migration. The channel is largely straight with low sinuosity. ~~No channel erosion was observed at the project site; therefore, the risk for channel migration is considered to be low~~Active bank erosion was observed on the right bank immediately downstream of the current culvert outlet, though the extent is localized to the outside meander bend. Given that the left bank floodplain bench is accessible during approximate 1-year flow events to alleviate erosive energy in the main channel, the risk of channel migration in the project reach is low.

2.8.6 Riparian Conditions, Large Wood, and Other Habitat Features

Clearcutting of forests throughout the region over the past century has resulted in major changes to the riparian systems along most streams and has created smaller, and less diverse riparian corridors and reduced stability of stream systems. The forest surrounding the upstream reach is a mature mixed forest consisting of alder, Western hemlock, Douglas fir and some western red cedars. ~~-~~The surrounding conifer forested area is secondary growth from previous timber harvest. The shrub understory is particularly dense at the upstream end of the surveyed reach where the mature tree canopy recedes back from the stream channel creating an open canopy. Shrub species were dominated by native species including salmonberry, willows, vine maple, salal, and sword fern.

Abundant LWM was observed throughout the upstream reach. There were over 50 significant pieces of LWM in the channel and on the banks, with several locations of log piles and log jams. These logs generally ranged in size from 8 to 36 inches in diameter and ~~also~~ included some root~~-~~wads. Approximately 50 feet upstream of the culvert, ~~Near the downstream end of the reach~~ there is a large LWM ~~pile~~ accumulation that completely ~~covers~~ spans the channel. Multiple flow paths have been created in and around this accumulation with a large pool forming just upstream of it.~~, with the stream flowing underneath in multiple paths. This is located approximately 50 feet upstream of the culvert and has caused a pool to form just upstream of it.~~ This along with ~~T~~two other stable log ~~piles~~ jams ~~are~~ located near the upstream extents of the survey, act to encourage bank overtopping during high flow events.~~. These three large log jams are potentially causing the flow in the stream to spread out into the~~into the ~~floodplains~~ at high flow events~~.~~

The downstream reach parallels highway 101 for the length of the field survey.~~ and t~~ The riparian corridor consists of a relatively narrow strip of mixed forest between the road prism and the stream including western hemlock, Douglas fir, and alder~~ between the road prism and the stream~~. The stream flows through a former timber harvested area and right bank riparian corridor is limited to a narrow strip approximately 30 feet in width by the edge of a relatively recent timber harvested cut-block with young, replanted conifer trees. Although the mature tree cover along both banks provides good shading for the stream, the constricted riparian corridor limits potential LWM recruitment. LWM is much less abundant in the downstream reach than upstream. There was only a single piece of significant LWM across the bankfull channel and a few areas with debris jams of branches and small material.

The downstream reach is ~~fairly uniform and straight~~composed of a straightened plane-bed channel~~,~~ with little habitat variability and devoid of deep pools. ~~are lacking throughout the surveyed reach.~~

No beaver activity was observed in the upstream or downstream reach.

3 Hydrology and Peak Flow Estimates

Harlow Creek is within an ungaged basin, with no long-term historical flow data available. A gaged basin with similar characteristics was not located. One previous hydrologic report was found for this basin; in 2017, a Basis of Design Report was written for U.S. 101 MP 146.85 Harlow Creek (WSDOT 2017). This report estimated a total drainage area of 3.97 square miles for the Harlow Creek watershed within the Quinault Reservation. Hydrology was analyzed using both the MGSFlood and USGS Regression equations methods; the USGS Regression equations were used because that method yielded more conservative flows. The USGS Regression equations (Mastin et al. 2016) for Region 4 were used to estimate peak flows at the U.S. 101 MP 142.48 crossing (Table 8~~Table 6~~). Inputs to the regression equation included basin size and mean annual precipitation. Harlow Creek at the crossing has a basin area of 0.31 square mile and a mean annual precipitation within the basin of 116.8 inches (PRISM Climate Group 2019). The basin was delineated from LiDAR data acquired from the Washington DNR LiDAR Portal (Watershed Sciences 2011) using Arc Hydro. The basin can be seen in Figure 40~~Figure 39~~. Flows were calculated based on the watershed as a whole~~,~~ and divided into the left UNT and mainstem Harlow Creek ~~and right tributaries~~ based on their respective drainage basins. The 2-year peak flow was estimated to be 37.6 cubic feet per second (cfs) and the 100-year flow was estimated to be 110.0 cfs. Summer low flow conditions are unknown. Average standard error varied from 50.5 to 58.0 percent. Standard error was not applied to the flows used in the hydraulic modeling. Table 8~~Table 6~~ shows the calculated peak flows for Harlow Creek at U.S. 101 MP 142.48. For more information on how the 2080 predicted 100-year flow was determined see Section 7.2.

Table 8: Peak flows for Harlow Creek at U.S. 101 MP 142.48

Mean recurrence interval (MRI) (years)	USGS regression equation (Region 4) (cfs)			Regression standard error (percent)
	Left UNT	Harlow Creek	Total	
2	6.7	30.9	37.6	52.5
10	10.9	50.7	61.6	50.5
25	12.8	59.8	72.6	51.7
50	14.4	66.9	81.3	52.9
100	16.1	75.0	91.1	54.2
500	19.5	90.5	110.0	58.0
2080 predicted 100-year			113.2	NA

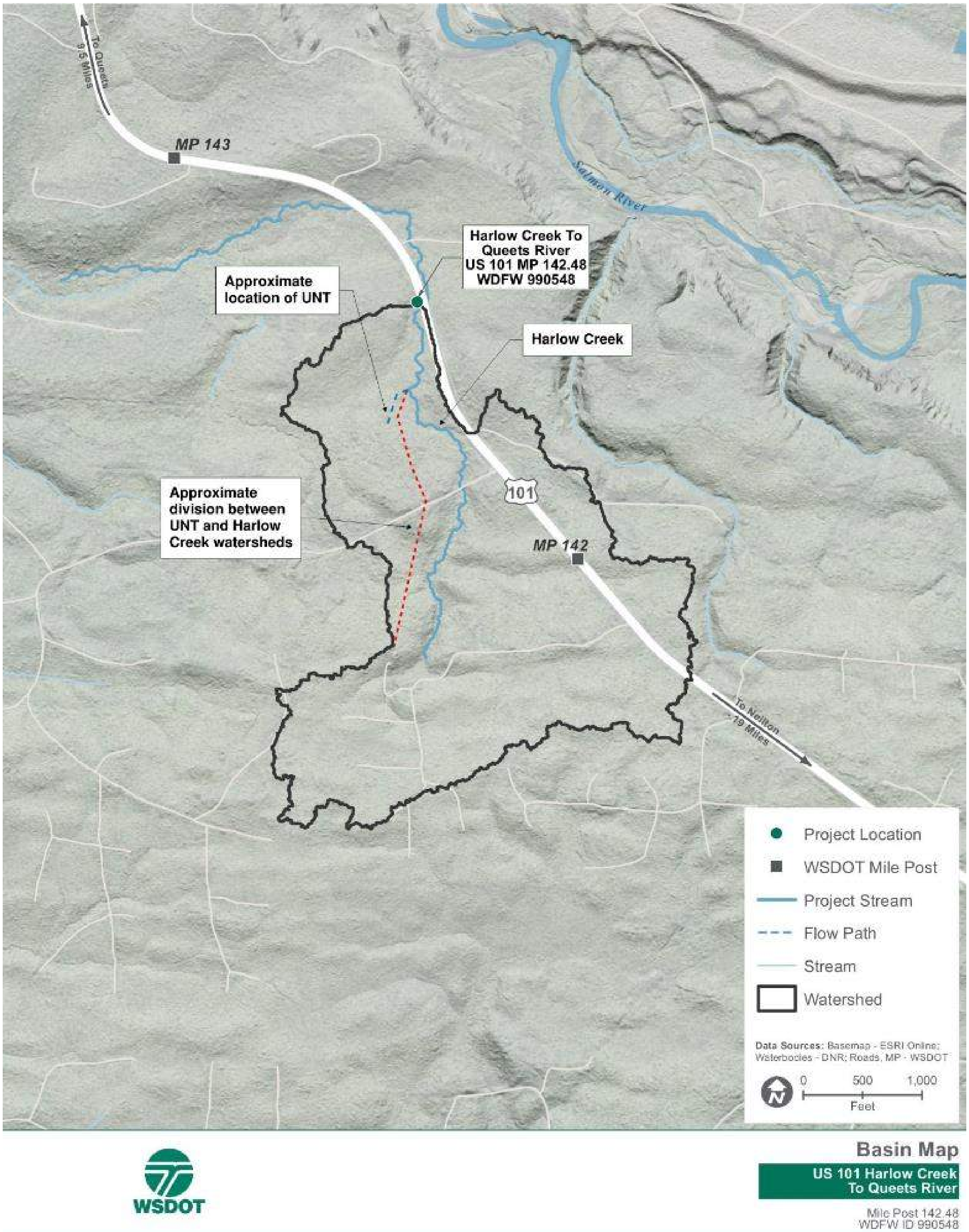


Figure <u>41</u>~~140~~: Basin map

4 Hydraulic Analysis and Design

The hydraulic analysis of the existing and proposed U.S. 101 MP 142.48 Harlow Creek crossing was performed using the U.S. Bureau of Reclamation's (USBR's) SRH-2D Version 3.2.4 computer program, a two-dimensional (2D) hydraulic and sediment transport numerical model (USBR 2017). Pre- and post-processing for this model was completed using SMS Version 13.0.12 (Aquaveo 2018).

Three scenarios were analyzed for determining stream characteristics for Harlow Creek with the SRH-2D models: (1) existing conditions with the 4-foot-diameter CMP, (2) natural conditions with the roadway embankment removed beyond the wetted extents and the channel graded to match the proposed grade, and (3) future conditions with the proposed 15-foot hydraulic opening.

4.1 Model Development

This section describes the development of the model used for the hydraulic analysis and design.

4.1.1 Topographic and Bathymetric Data

The channel geometry data in the model were obtained from the MicroStation and InRoads files supplied by the Project Engineer's Office (PEO), which were developed from topographic surveys performed by surveyors hired by WSDOT prior to March 13, 2020. The survey data were supplemented with LiDAR data (Watershed Sciences 2011). The LiDAR data were collected on the Quinault River Basin survey area for the Puget Sound LiDAR Consortium and the Quinault Indian Nation over approximately 370 square miles. Both airborne survey and ground survey were used to gather information for this deliverable.

Proposed channel geometry was developed from the proposed grading surface created by HDR. All survey and LiDAR information is referenced against the North American Vertical Datum of 1988 (NAVD88) and tied into the WSDOT grid using the NAD83 (1991 HARN) Horizontal Datum.

4.1.2 Model Extent and Computational Mesh

The hydraulic model upstream extents begin with the detailed survey data and start approximately 240 feet upstream of the existing culvert inlet. LiDAR data are stitched in as well to the east and west of the upstream survey extents to capture the unconfined channel. The hydraulic model downstream extents end with LiDAR beyond the survey data. The detailed survey data end approximately 230 feet downstream of the existing culvert outlet, measured along the channel centerline. LiDAR data continue for another 35 feet to accurately capture the flow leaving the model. In addition, LiDAR data are used to detail east and west of the downstream boundary condition because some flow exits the model in a different location from the surveyed downstream end of the reach.

The computational mesh elements are a combination of patched (quadrilateral) and paved (triangular) elements. Finer resolution was used in the channel (with the exception of large pools) and wherever else it was simple to use quadrilateral elements, while larger elements were used in the floodplain. The existing-conditions mesh covers a total area of 122,000 SF, with 5,575 quadrilateral and 17,979 triangular elements (Figure 41~~Figure 40~~). The natural-conditions mesh, simulating what the creek would look like in its existing alignment without the roadway, covers a total area of 122,000 SF, with 5,492 quadrilateral and 18,283 triangular elements (see Figure 42~~Figure 41~~). The proposed-conditions mesh covers a total area of 122,000 SF, with 5,059 quadrilateral and 18,313 triangular elements (see Figure 43~~Figure 42~~).

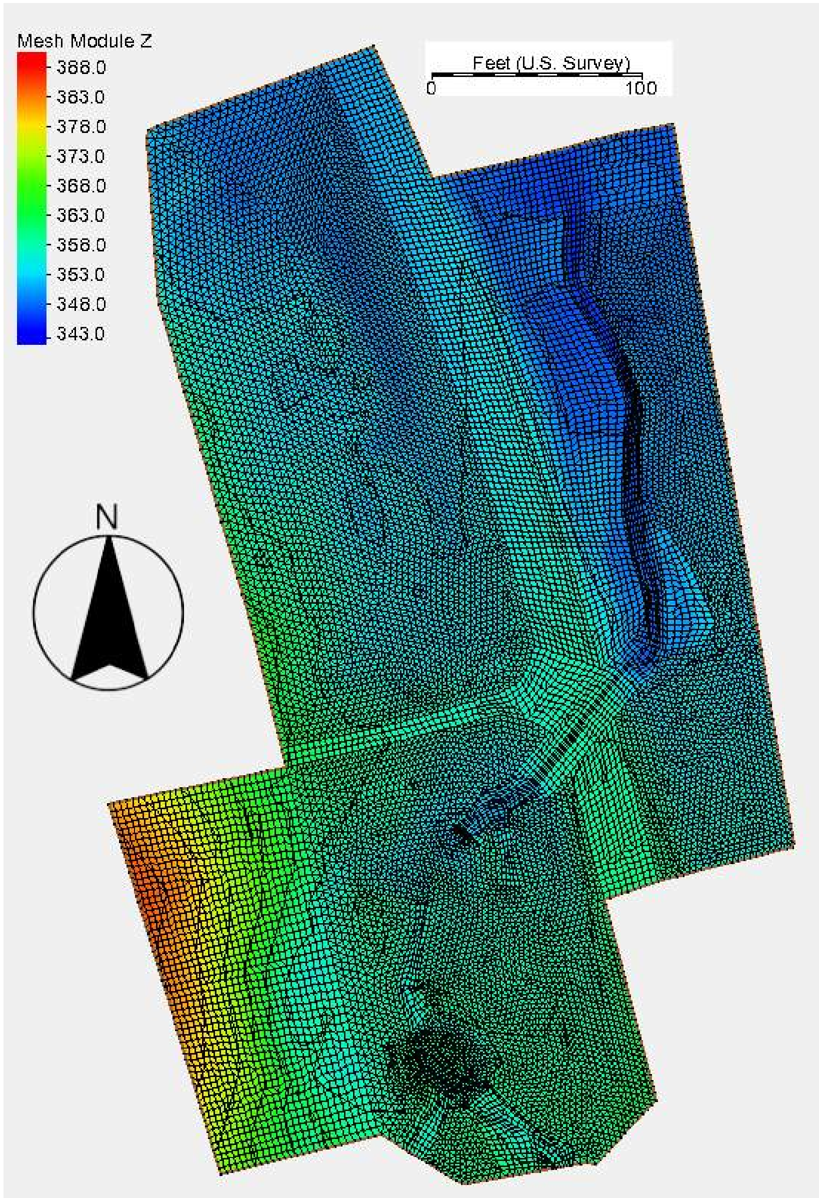
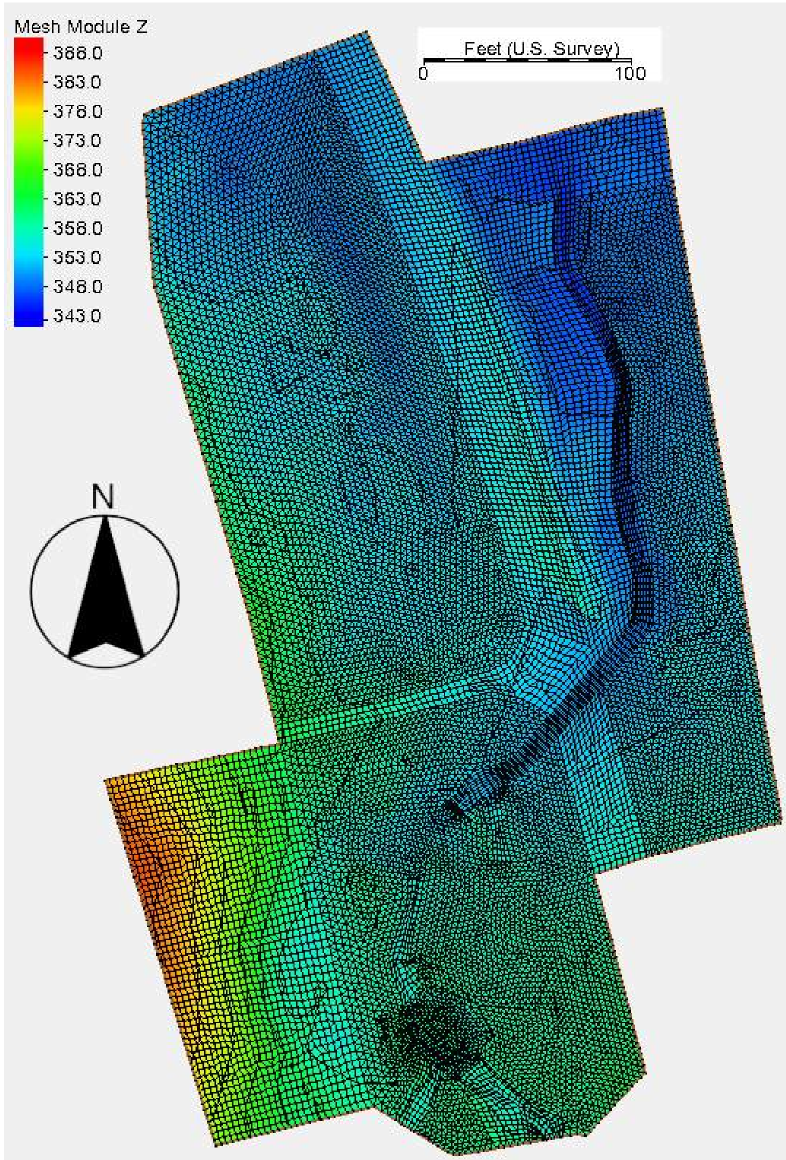


Figure 4242~~41~~: Existing-conditions computational mesh with underlying terrain


Mesh Module Z
388.0
383.0
378.0
373.0
368.0
363.0
358.0
353.0
348.0
343.0
Feet (U.S. Survey)
0
100
N

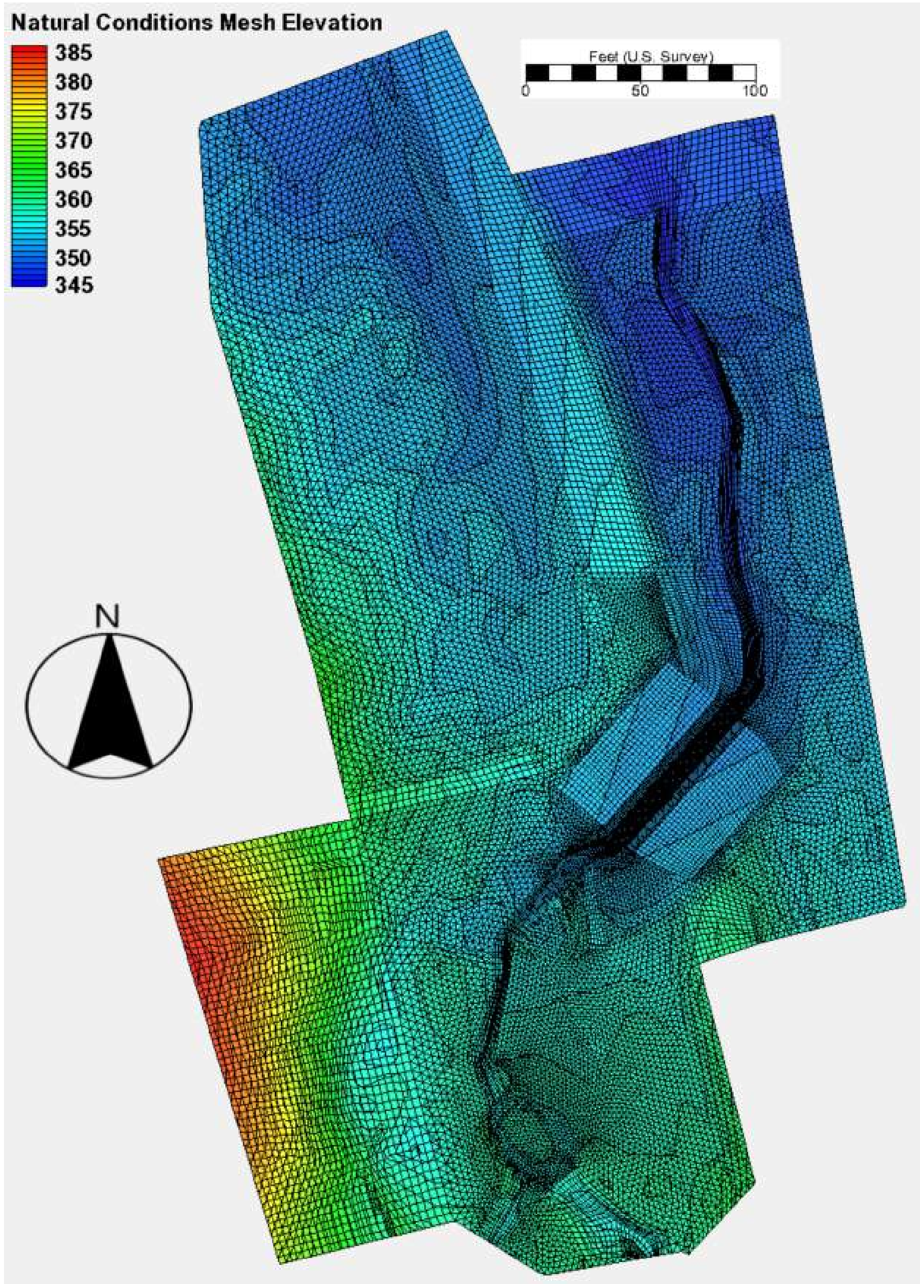
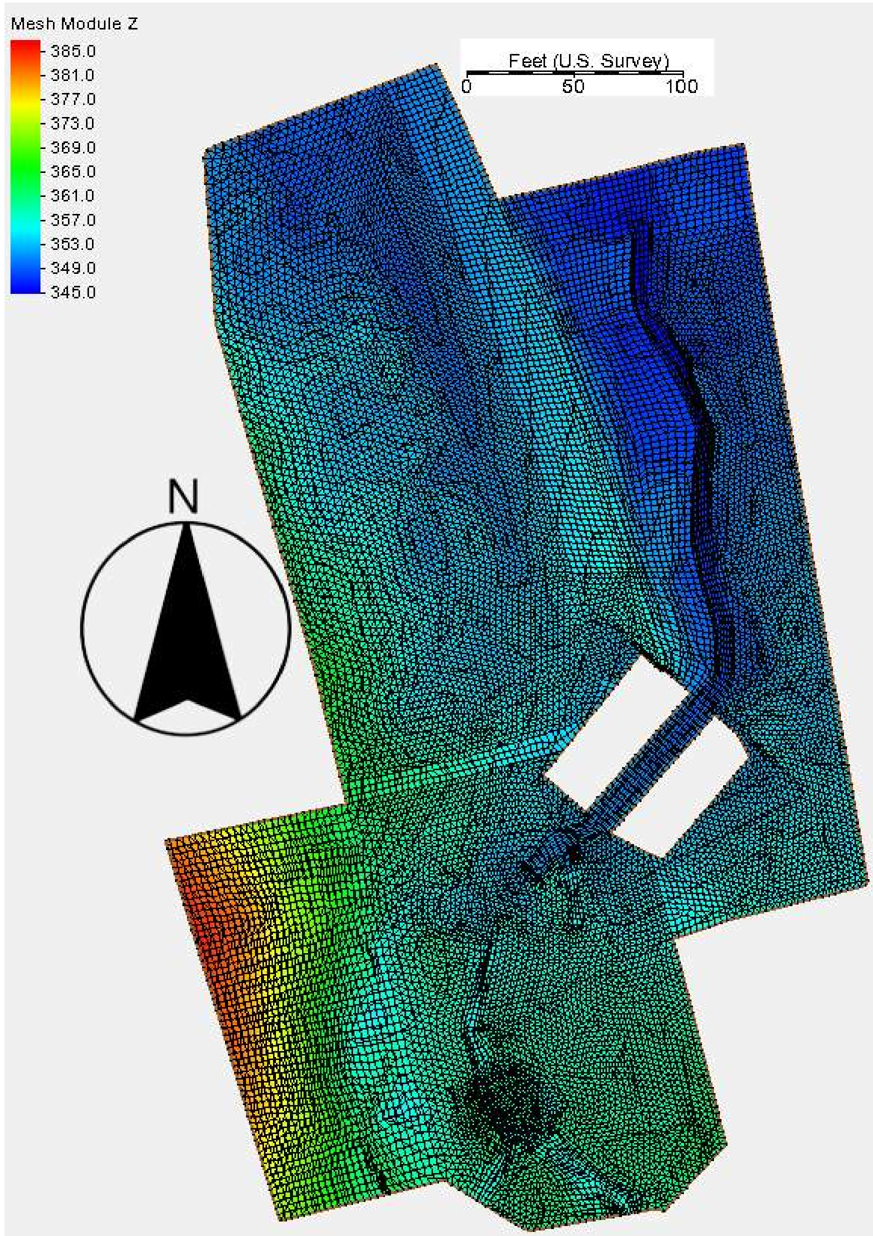


Figure 43~~4342~~: Natural-conditions computational mesh with underlying terrain


Mesh Module Z
385.0
381.0
377.0
373.0
369.0
365.0
361.0
357.0
353.0
349.0
345.0
Feet (U.S. Survey)
0
50
100
N

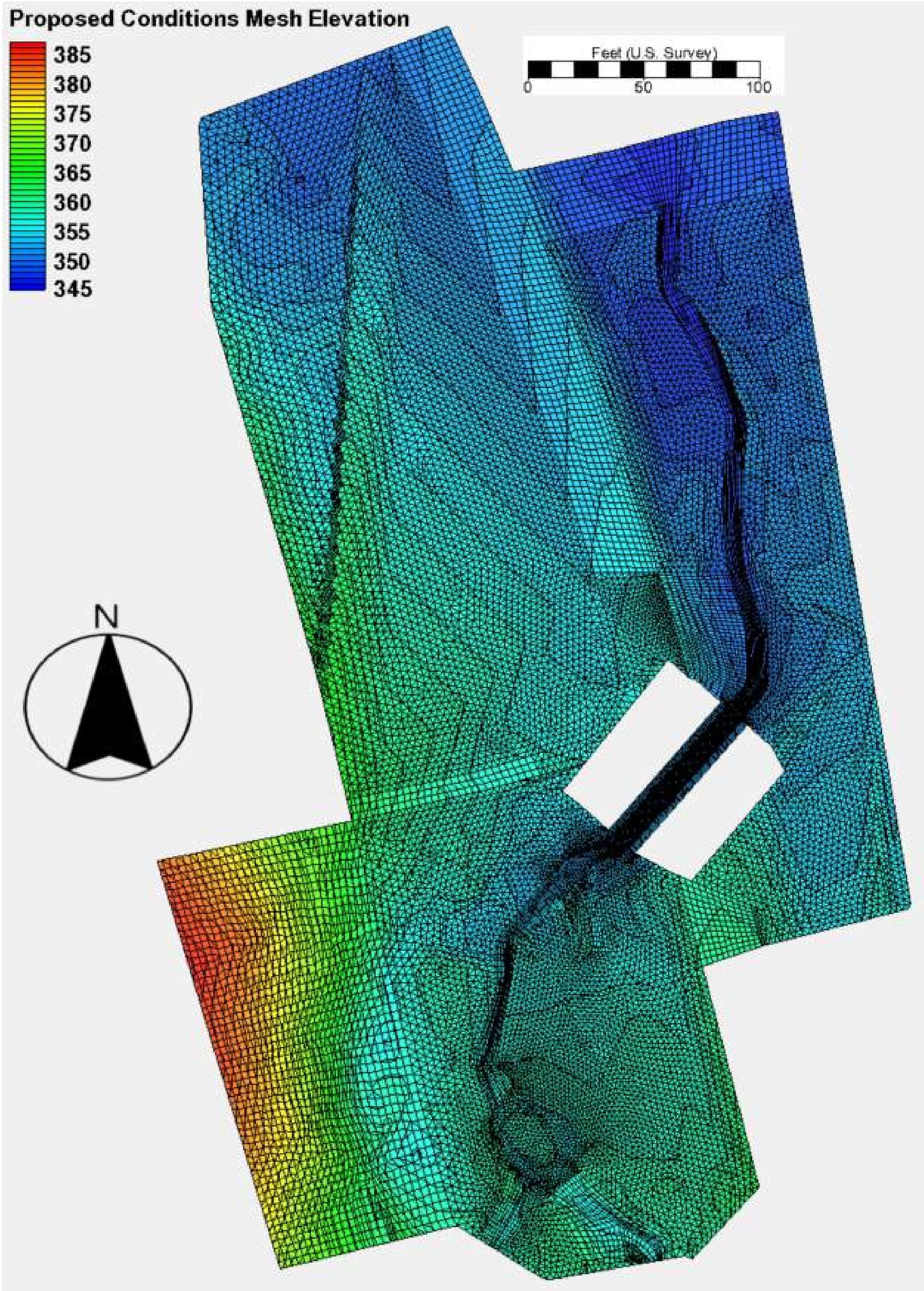


Figure ~~444443~~: Proposed-conditions computational mesh with underlying terrain

4.1.3 Materials/Roughness

Manning's n~~-~~-values (roughness) were estimated based on site observations, aerial photography, and standard engineering values (Chow 1959) and are summarized below (Table 9~~Table 7~~). Roughness in the upstream and downstream floodplain are characterized by 0.12—heavy stands of timber, because of the densely forested landscape. The floodplain near the reference reach is characterized by 0.10, because the forest and shrubs in this location were less dense than elsewhere in the reach. The downstream channel is 0.045, defining the main channel as clean and winding with some pools, shoals, weeds, and stones. The upstream channel is 0.06 because of the amount of LWM found in the channel. These values are listed in Table 9~~Table 7~~. Roughness values between existing and proposed conditions remained the same except for material inside the proposed structure and the ~~upstream~~ downstream grading; see Figure 44~~Figure 43~~ and Figure 45~~Figure 44~~ for a spatial distribution of hydraulic roughness coefficient values.

Table 9: Manning's n-value hydraulic roughness coefficient values used in the SRH-2D model

Land cover type	Manning's n
Upstream Channel	0.~~060~~675
Downstream Channel ~~/ Proposed Channel~~	0.045
Proposed Channel	0.060
Floodplains	0.12
Reference Reach Floodplains	0.10
Roadway	0.02

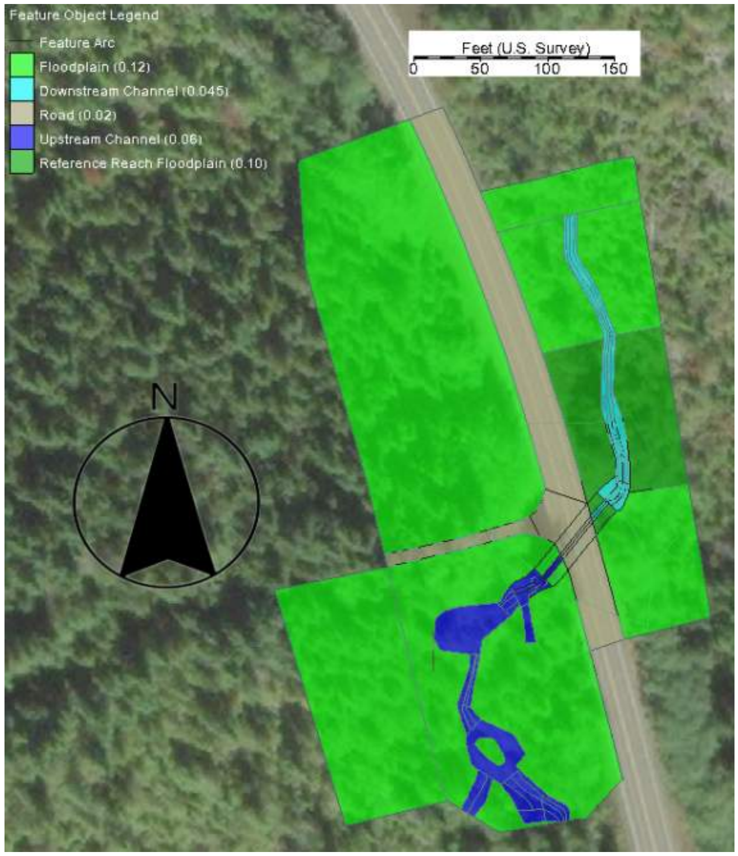


Figure 45~~4544~~: Spatial distribution of roughness values in SRH-2D existing-conditions model

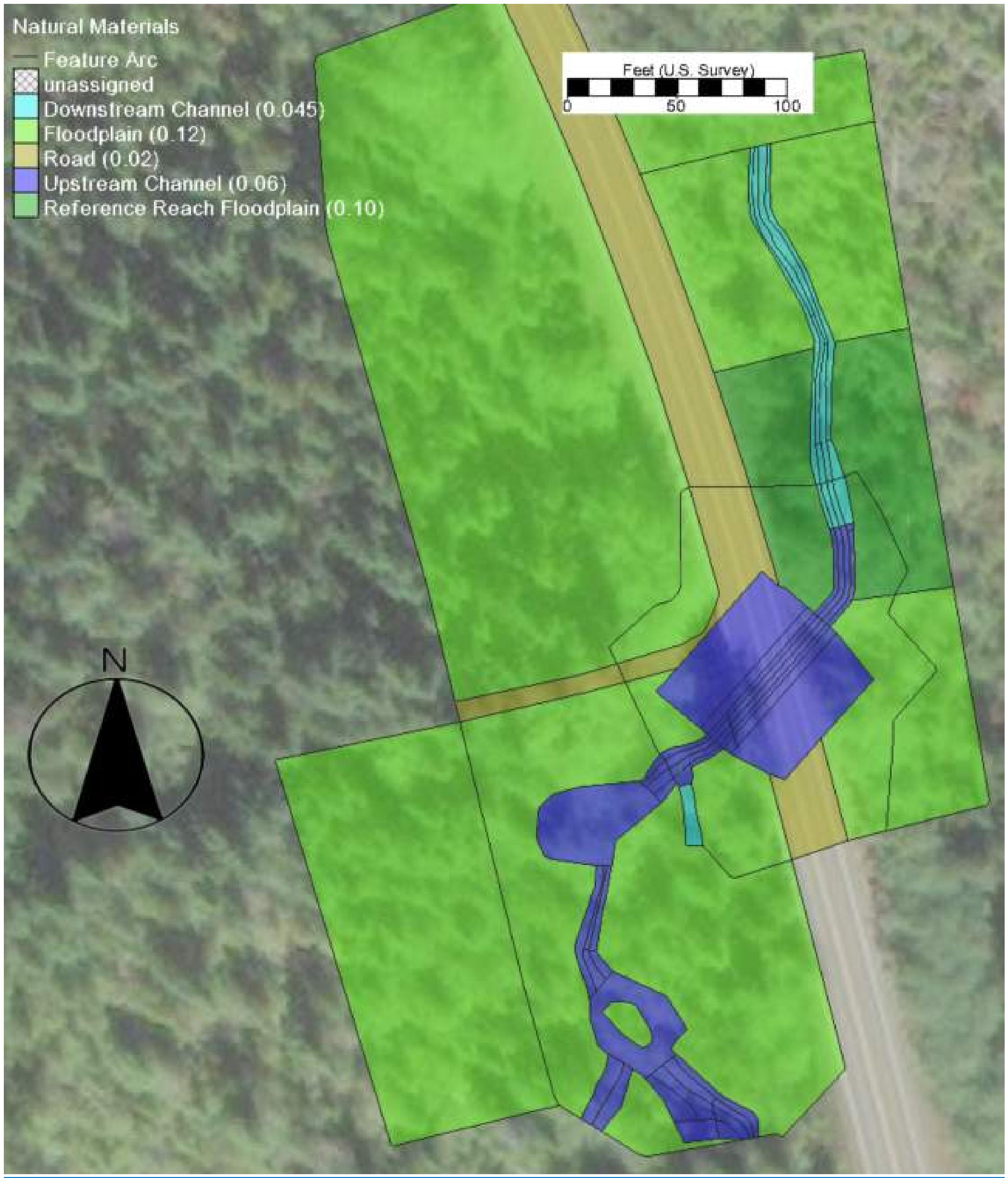
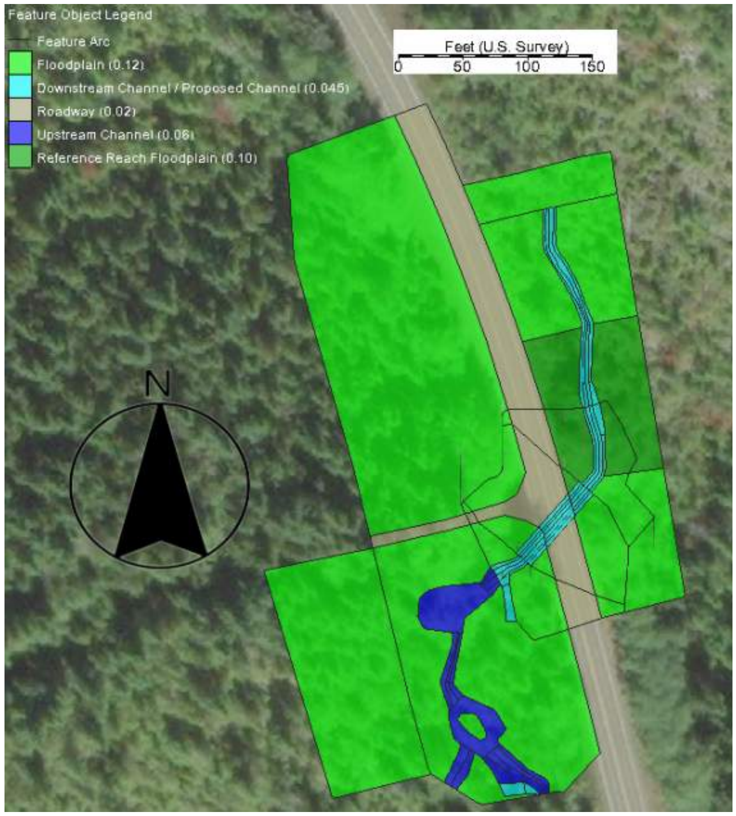


Figure 46: Spatial distribution of roughness values in SRH-2D natural-conditions model



Feature Object Legend
Feature Arc
Floodplain (0.12)
Downstream Channel / Proposed Channel (0.045)
Roadway (0.02)
Upstream Channel (0.06)
Reference Reach Floodplain (0.10)
Feet (U.S. Survey)
0
50
100
150
N

Figure 47~~4745~~: Spatial distribution of roughness values in SRH-2D proposed-conditions model

4.1.4 Boundary Conditions

Model simulations were performed using a quasi-steady inflow, with the design ~~constant~~ discharges ~~ranging from the (~~2-year to 500-year peak flow events) run to equilibrate within the model domain ~~summarized in Section 3~~. External boundary conditions were applied at the upstream and downstream extents of the model domain and remained the same between the existing- and proposed-conditions runs. Two ~~constant~~ inflow ~~rates~~ hydrographs were specified at the upstream external boundary condition to represent the two tributaries, while two normal depth rating curves were specified at the downstream boundary: one at the channel exit, and one across the roadway for roadside drainage where flow is also leaving the existing-conditions model at higher flow events. The downstream normal depth boundary condition rating curve at the channel exit was developed within SMS using the existing terrain, assuming a downstream slope of 2.5 percent as measured from the survey and a composite roughness of 0.09. See Figure 46~~Figure 45~~ for the channel downstream boundary conditions and Figure 47~~Figure 46~~ for the resulting rating curve. The downstream normal depth boundary condition rating curve at the roadside drainage was developed within SMS using the existing terrain, assuming a downstream slope of 2.0 percent as measured from LiDAR and a composite roughness of 0.12. See Figure 48~~Figure 47~~ for the roadside drainage downstream boundary conditions and Figure 49~~Figure 48~~ for the resulting rating curve. A sensitivity analysis on the downstream boundary condition was performed to obtain an accurate representation of the water surface profile and to determine if the boundary condition assumption affected hydraulics within the U.S. 101 crossing project extents. Model simulations were run for a sufficiently long duration until the results stabilized across the model domain.

An HY-8 internal boundary condition was specified in the existing-conditions model to represent the existing circular CMP culvert crossing. The existing crossing was modeled as a 4-foot-diameter circular pipe within HY-8. A Manning's roughness n-value of 0.024 was assigned to the culvert. The culvert was assumed to be unobstructed and free from any stream material within the barrel. See Figure 50~~Figure 49~~ for the HY-8 boundary conditions. See Figure 51~~Figure 50~~ for a map showing the location of each boundary condition in the existing-conditions model. A ~~symmetry~~wall (no-slip) boundary condition was specified in the proposed-conditions model to ~~better~~ represent flow inside the proposed structure.

See Figure 52~~Figure 51~~ for a map showing the location of each boundary condition in the natural-conditions model.

~~A symmetry (slip) boundary condition was specified in the proposed-conditions model to better represent flow inside the proposed structure. Under default conditions, SMS assumes a no-slip (0 ft/s) condition at the edges of the mesh. The boundary layer of 0 ft/s would be very thin against the smooth structure surface. The mesh is too coarse to accurately capture the boundary layer; therefore, it is more appropriate to use a slip boundary condition, which does not force velocities to 0 ft/s at the mesh boundary. See Figure 52 for a map showing the location of each boundary condition in the proposed-conditions model.~~

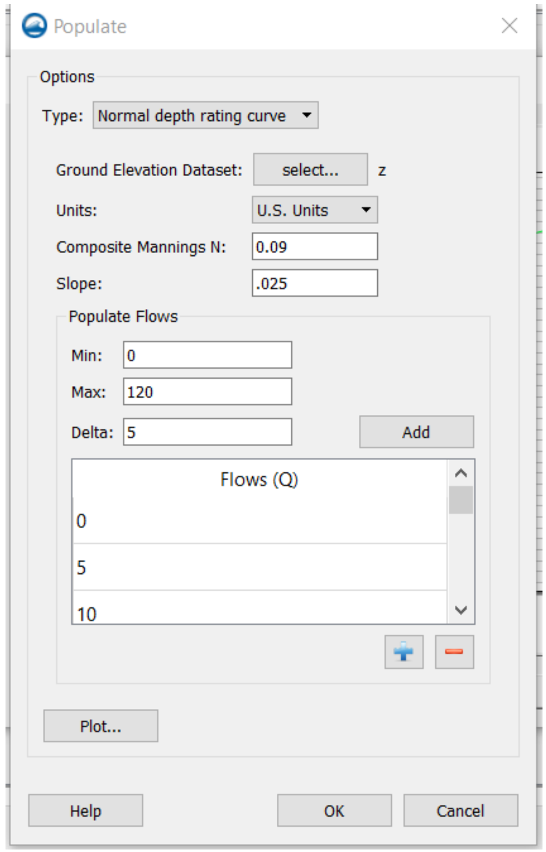


Figure 48~~46~~: Channel downstream boundary condition input

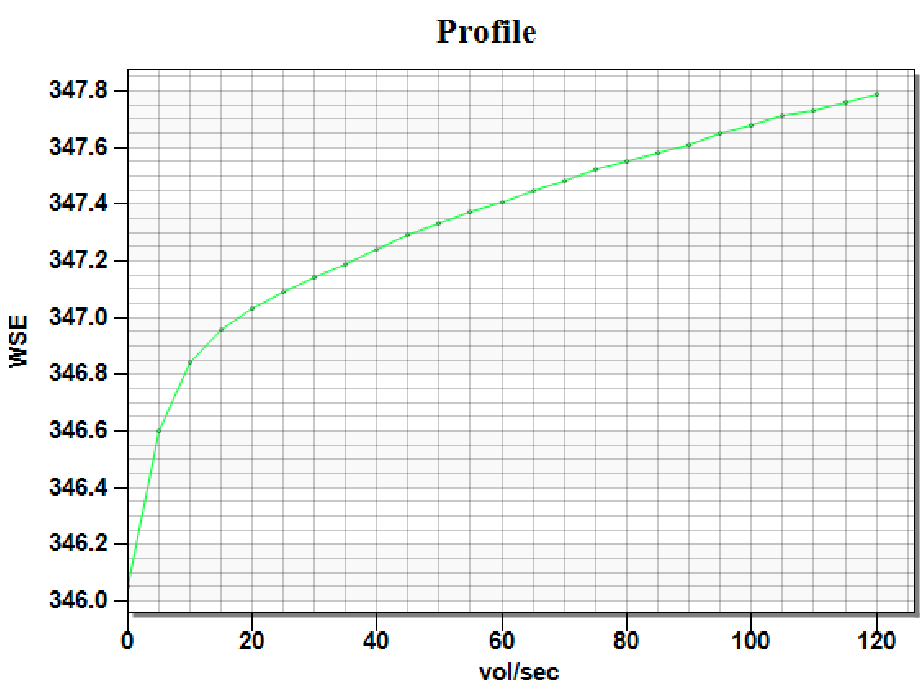


Figure 49~~47~~: Channel downstream normal depth rating curve

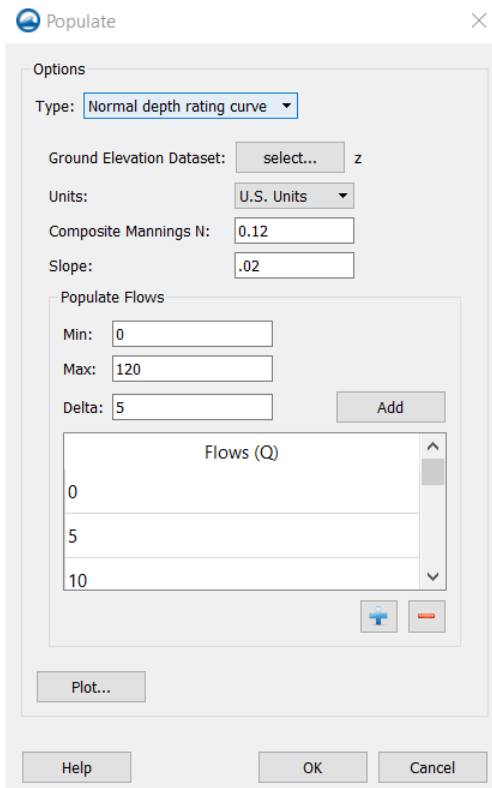


Figure 50~~48~~: Roadside drainage downstream boundary condition input

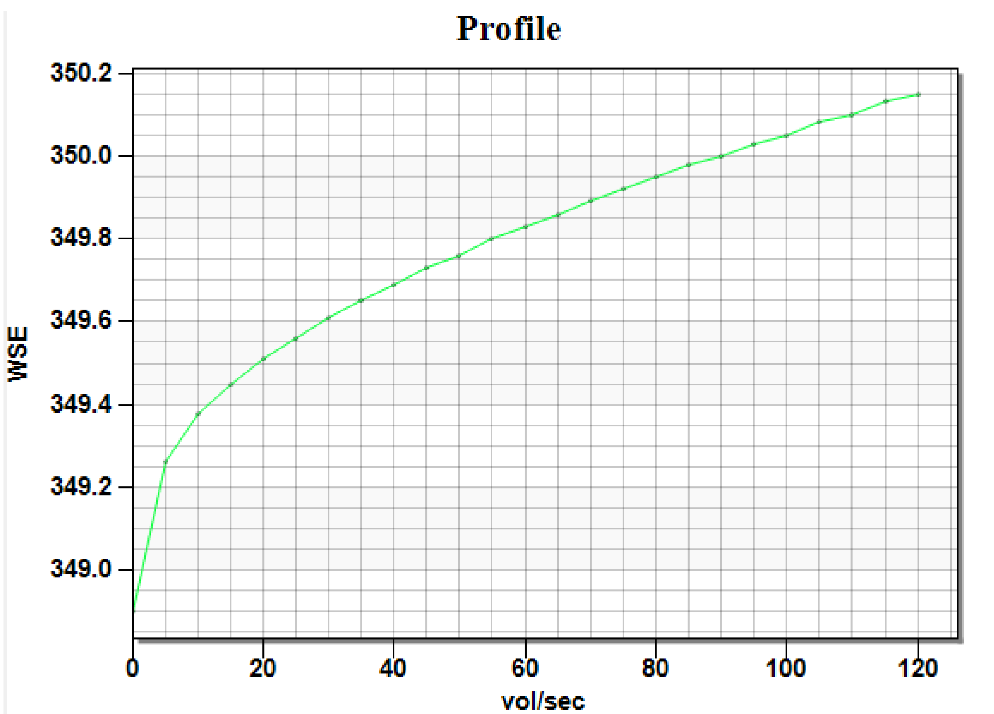


Figure 51~~49~~: Roadside drainage downstream normal depth rating curve

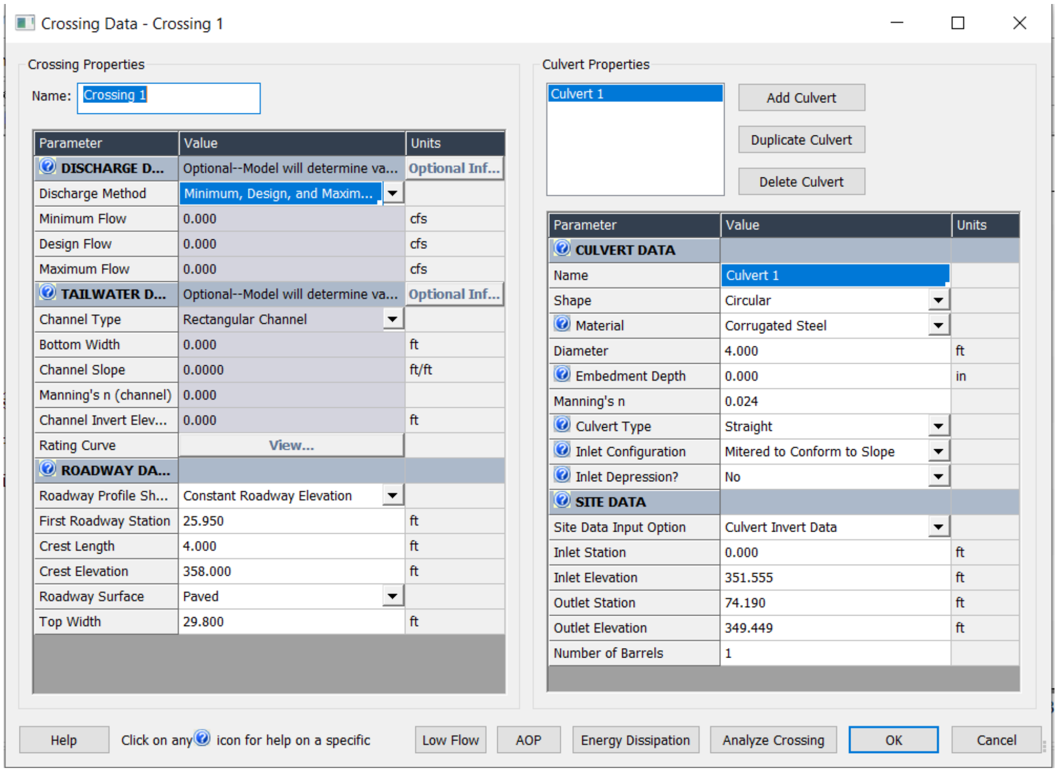


Figure 52~~5250~~: HY-8 Culvert parameters for existing conditions simulation

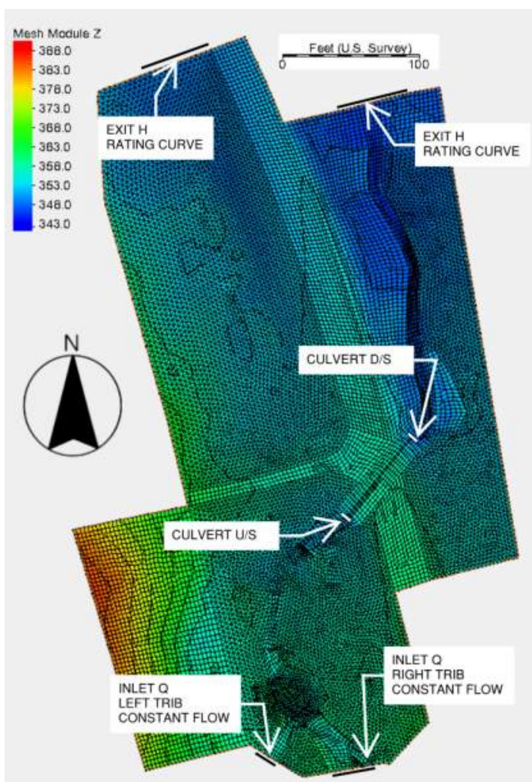


Figure 53~~5351~~: Location of boundary conditions for the existing-conditions model

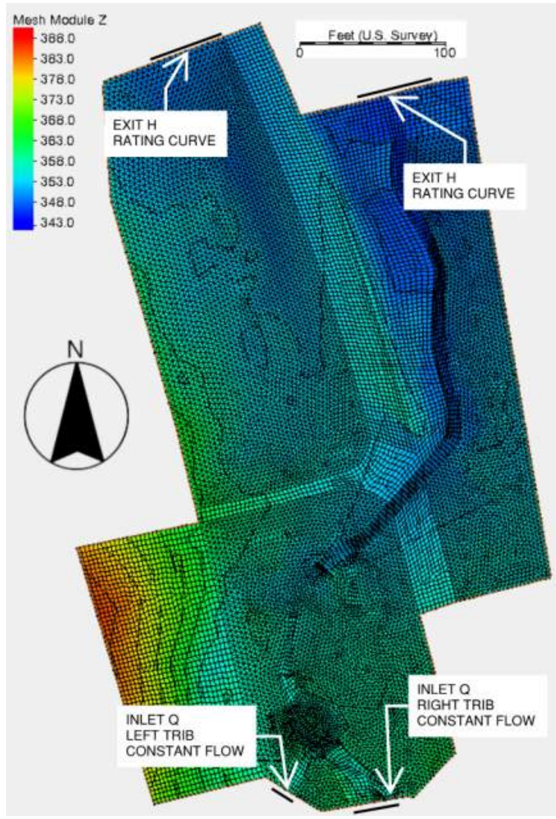


Figure 54~~5452~~: Location of boundary conditions for the natural-conditions model

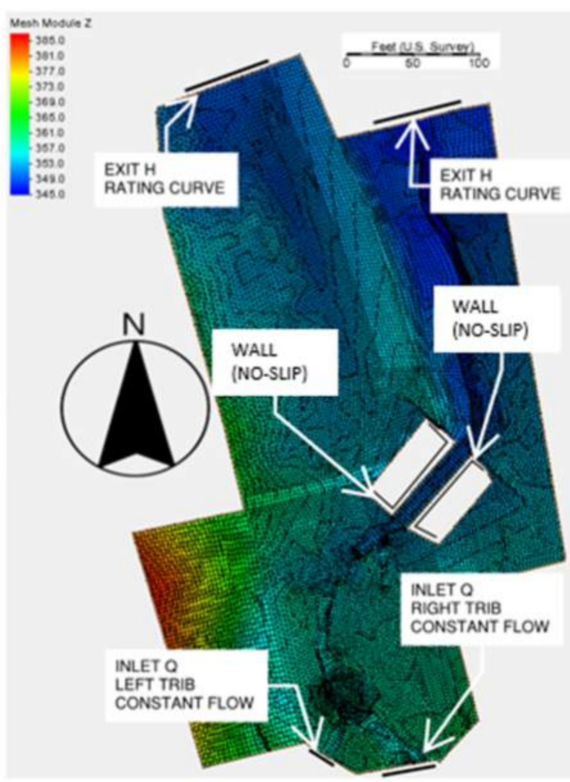


Figure 55~~5553~~: Location of boundary conditions for the proposed-conditions model

4.1.5 Model Run Controls

The model controls used in the simulation for every flow event are shown in Figure 54~~Figure 53~~. The result output frequency used was once per minute (0.016 hour) to begin with to troubleshoot the ~~model, and~~model and graduated to every 15 minutes (0.25 hour) once the model was stable.

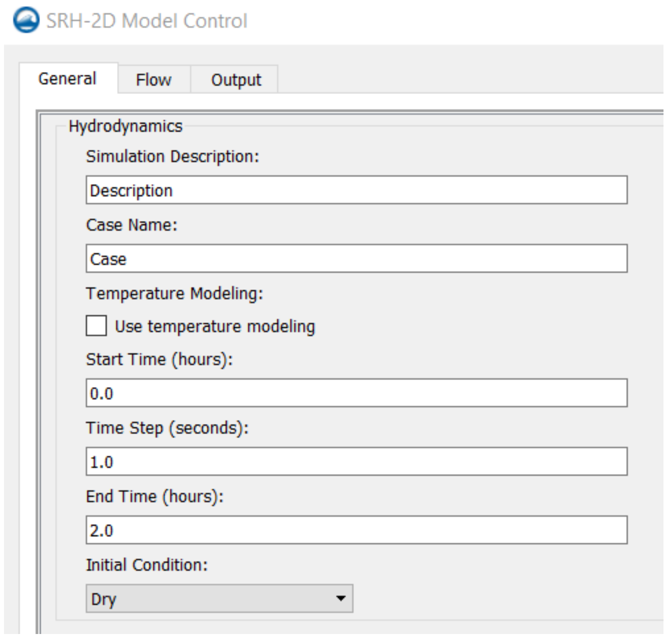


Figure 56~~5654~~: Model controls

4.1.6 Model Assumptions and Limitations

The SRH-2D hydraulic model was developed to determine the minimum hydraulic structure opening, establish the proposed structure low chord elevation (and associated freeboard), and characterize hydraulic parameters used to design the crossing. The use of a constant inflow rate is an appropriate assumption to meet the model objectives. Using a constant inflow rate provides a conservative estimate of inundation extents and water surface elevation (WSEL) associated with a given peak flow, which is used to determine the structure size and low chord.

Using the approach described in this study, each scenario is run for a sufficient time to fill storage areas and for water surface elevations to stabilize until flow upstream equals flow downstream. This modeling method does not account for the attenuation of peak flows between the actual upstream and downstream hydrographs, in particular with a large amount of storage upstream of the existing undersized culvert. During an actual runoff event, it is unlikely that the area upstream of the culvert would fill up entirely. An unsteady simulation could be used to route a hydrograph through the model to estimate peak flow attenuation for existing and proposed conditions. During an unsteady simulation, the areas upstream of the existing culvert would act as storage and, as a result, the flow downstream of the crossing would likely be less than the current design peak flow event. Estimates of ~~the~~ downstream increases to water surface elevation and flow based on the constant inflow model results may then underestimate the downstream flood impacts. An unsteady analysis is outside the current scope of this preliminary study~~,~~ but could be considered at a later stage of design. Therefore, the changes to the peak flow rate downstream of the project cannot be quantified with this approach.

The model results and recommendations in this report are based on the conditions of the project site and the associated watershed at the time of this study. Any modifications to the site, man-made or natural, could alter the analysis, findings, and recommendations contained herein and could invalidate the analysis, findings, and recommendations. Site conditions, completion of upstream or downstream projects, upstream or downstream land use changes, climate changes, vegetation changes, maintenance practice changes, or other factors may change over time. Additional analysis or updates may be required in the future as a result of these changes.

4.2 Existing-Conditions Model Results

Locations of the cross sections used for results reporting for existing-, natural-, and proposed-conditions models are shown in Figure 55~~Figure 54~~. Three cross sections are located upstream and three are located downstream, with one in the center of the existing culvert and proposed structure. The longitudinal profile stationing can be seen in Figure 56~~Figure 55~~.

Existing-conditions hydraulic results across the main channel are summarized for the upstream and downstream cross sections in Table 10~~Table 8~~. Under existing conditions, the culvert does not have capacity to convey the design flow. This causes backwater to fill the area upstream for the range of flows simulated (in Figure 57~~Figure 56~~). Pressure flow conditions first occur at the 2-year flow event, when the headwater elevation exceeds 354.2 feet. The U.S. 101 roadway was not overtopped at the project culvert, but a smaller unnamed roadway ~~heading~~ aligned due west ~~off~~ of U.S. 101 is overtop~~s~~ped at both the 100-year and 500-year events leading some flow to bypass the culvert.

Typical cross sections for downstream and upstream are found in Figure 58~~Figure 57~~ and Figure 59~~Figure 58~~, respectively. The downstream cross section shows a channel that, while confined, has an accessible floodplain. The upstream cross section shows an unconfined channel spreading flow into the floodplains at low flows. All cross sections were drawn perpendicular to flow. The 100-year velocity map for existing conditions can be seen in Figure 60~~Figure 59~~. All cross sections are presented in Appendix C.

As a result of the backwater associated with the 48-inch-diameter culvert, the upstream depths are greater than the downstream reach. In addition, the cross section directly upstream of the structure (within the limits of backwater) has ~~smaller~~ lower velocities and shear stresses than the other cross sections throughout the stream. Despite an average slope of approximately 3 percent compared to the downstream slope of 1 percent, the upstream reach cross sections have ~~smaller~~ lower velocities than the downstream reach because existing log jams cause the flow to spread out across the floodplains outside of the main channel. Downstream velocities range from 3.0 ft/s to 5.8 ft/s during all flow events, while upstream velocities range from 1.0 ft/s (~~because of~~due to backwater conditions) to 4.1 ft/s during all flow events. Shear values remained consistent throughout the entire stream reach; they ranged from 0.6 to 1.6 pound per square foot (lb/SF) in the downstream cross sections, and from <0.1 to 1.8 lb/SF in the upstream cross sections. When looking at the entire model domain, the ~~largest~~ highest velocities occurred at the culvert outlet and at the cross section farthest downstream, where no backwater is ~~present~~present, and the flow is more confined than in the upstream cross sections. Figure 30 shows the 100-year velocity map with the cross-~~-~~section locations depicted. Average velocities across the main channel, left overbank (LOB), and right overbank (ROB) of each cross section for the 100-year flow are shown in Table 11~~Table 9~~.

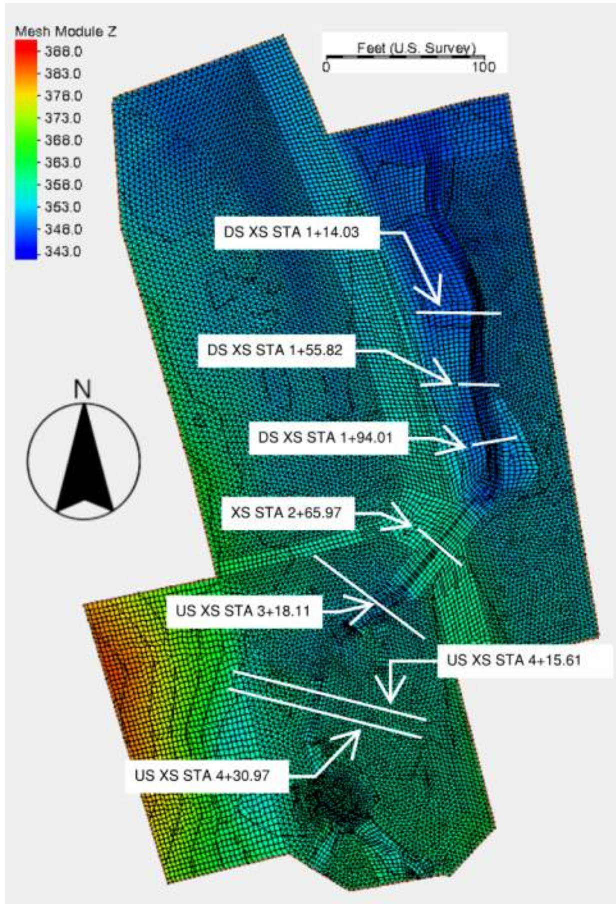


Figure ~~5755~~57: Locations of cross sections used for results reporting for existing-, natural-, and proposed-conditions models

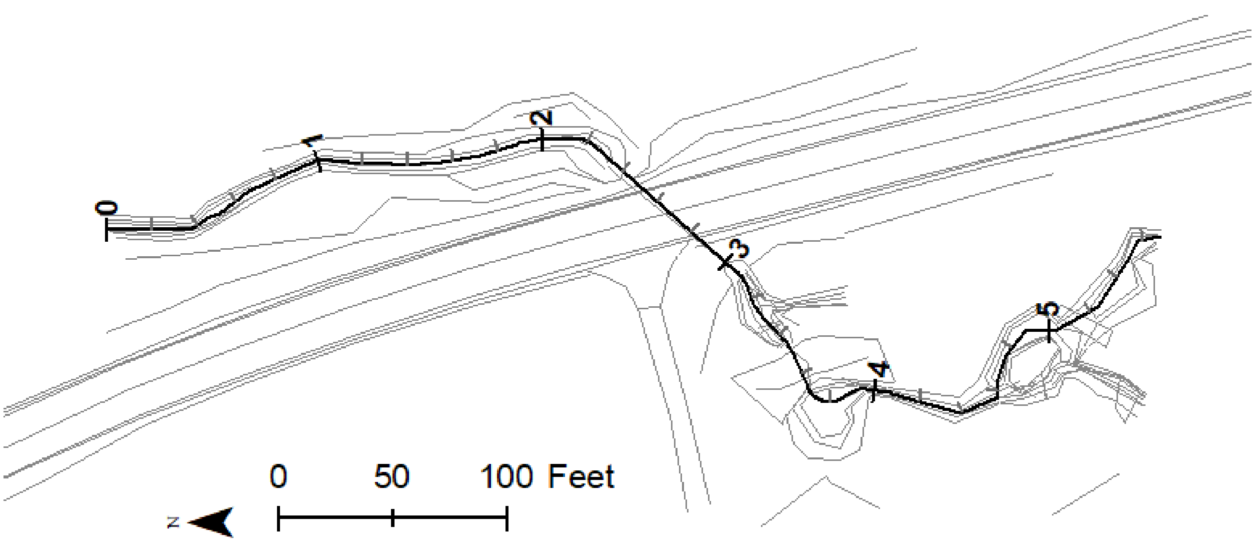


Figure ~~5856~~58: Longitudinal profile stationing for existing, natural, and proposed conditions

Table 10: Hydraulic results for existing conditions within main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	500-year
Average water surface elevation (ft)	1+14.03	348.3	348.9	349.0
	1+55.82	348.8	349.8	349.8
	1+94.01	349.2	350.0	350.0
	2+65.97	353.4	354.4	354.8
	3+18.11	354.3	356.6	356.9
	4+15.61	356.9	357.2	357.3
	4+30.97	357.3	357.6	357.7
Maximum water depth (ft)	1+14.03	1.7	2.4	2.4
	1+55.82	1.7	2.7	2.8
	1+94.01	1.6	2.4	2.4
	2+65.97	1.8	2.8	3.2
	3+18.11	3.4	5.7	5.9
	4+15.61	2.2	2.6	2.7
	4+30.97	2.1	2.5	2.6
Average velocity magnitude (ft/s)	1+14.03	4.1	5.7	5.8
	1+55.82	3.0	3.8	3.8
	1+94.01	3.6	4.8	4.8
	2+65.97	6.8	9.5	10.4
	3+18.11	1.2	1.0	1.0
	4+15.61	3.3	4.1	4.1
	4+30.97	2.6	3.7	3.8
Average shear stress (lb/SF)	1+14.03	1.0	1.6	1.6
	1+55.82	0.6	0.6	0.6
	1+94.01	0.9	1.2	1.2
	2+65.97	0.8	1.4	1.6
	3+18.11	<0.1	<0.1	<0.1
	4+15.61	1.3	1.8	1.8
	4+30.97	0.9	1.3	1.4

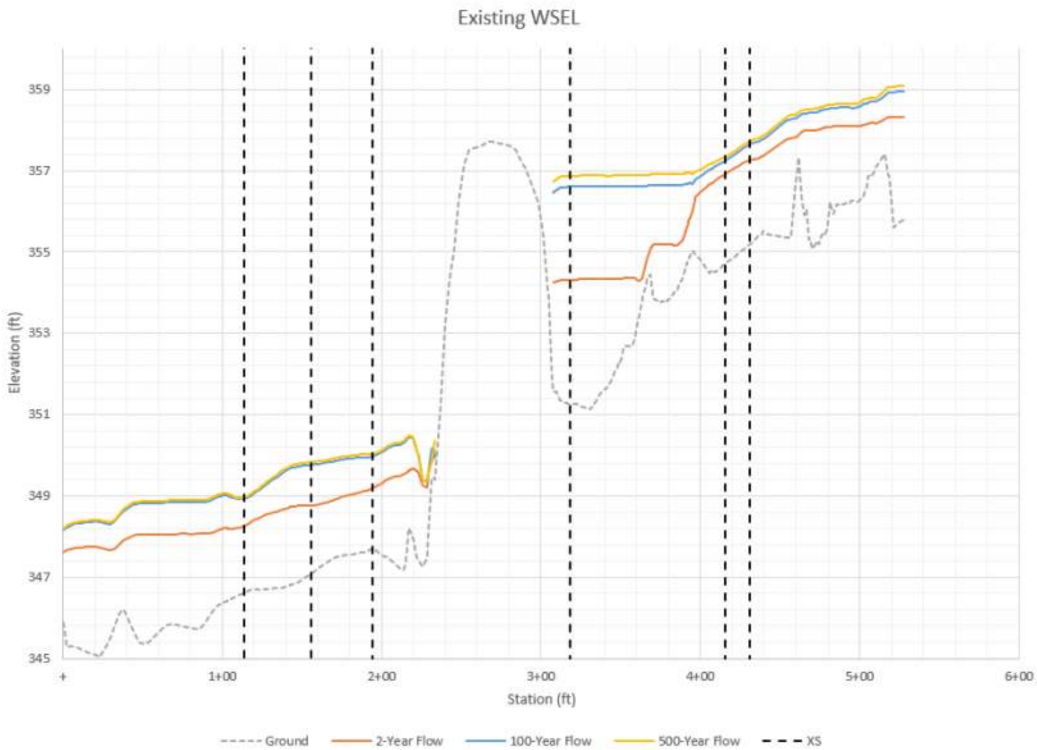


Figure 5959~~57~~: Existing-conditions water surface profiles

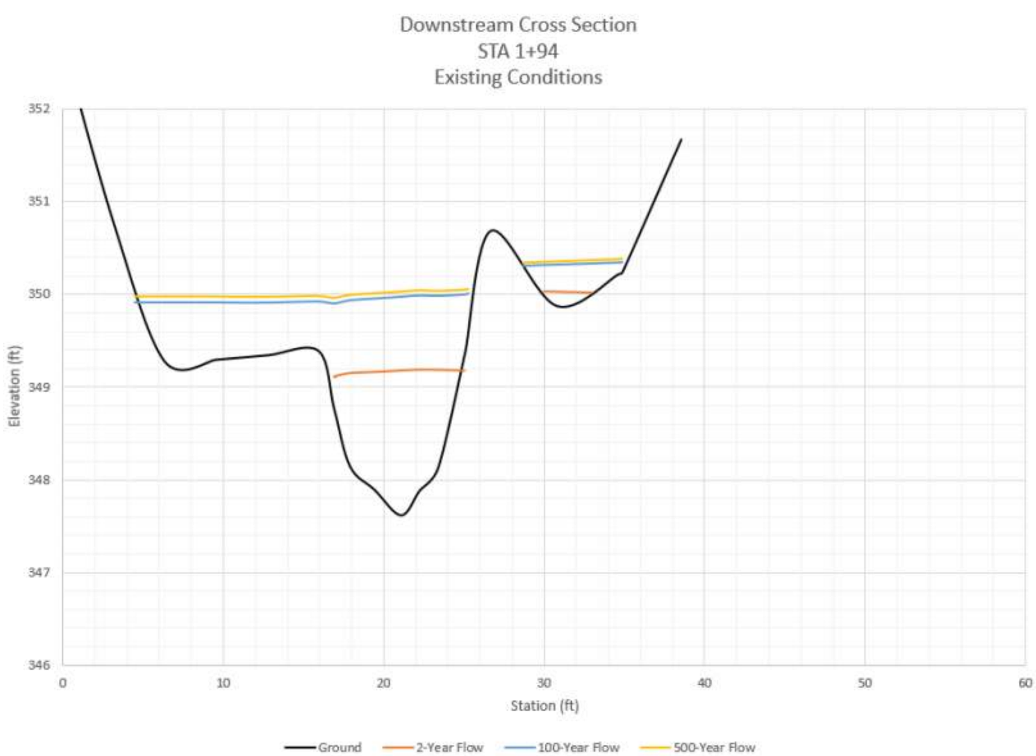


Figure 6060~~58~~: Typical downstream existing-conditions channel cross section (STA 1+94)

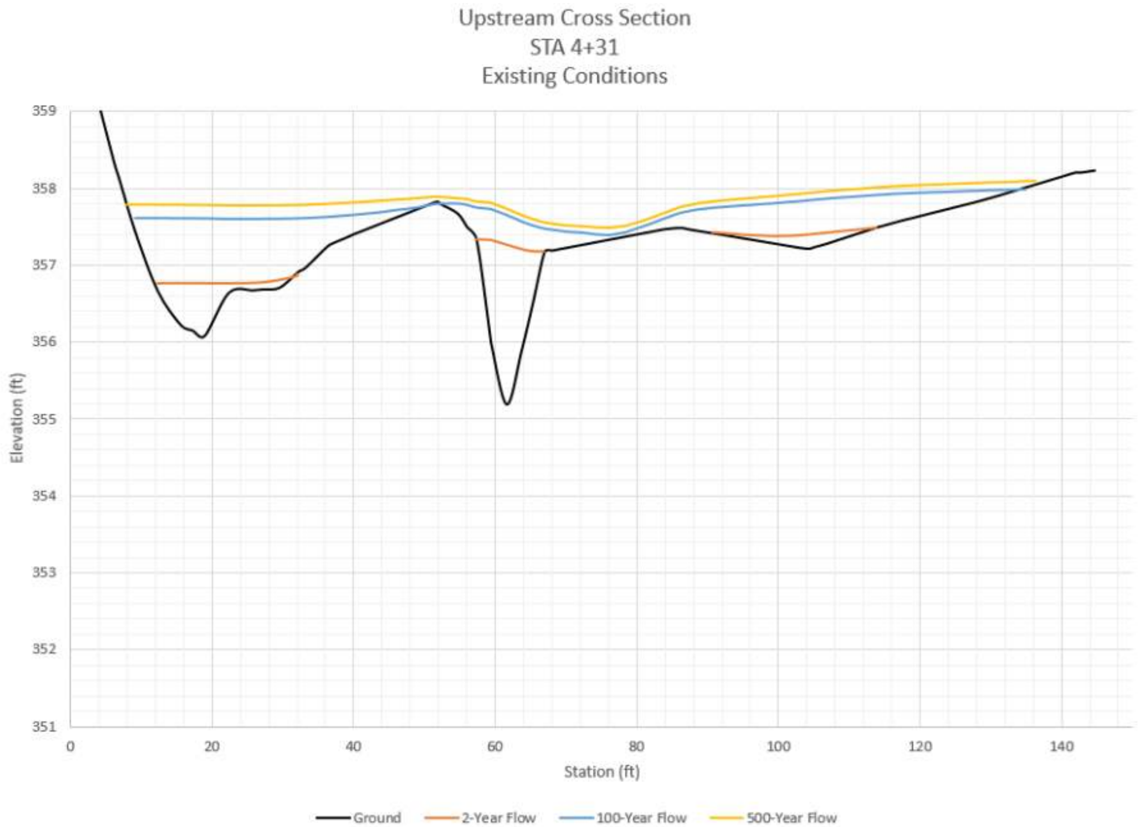


Figure 6161~~59~~: Typical upstream existing-conditions channel cross section (STA 4+31)

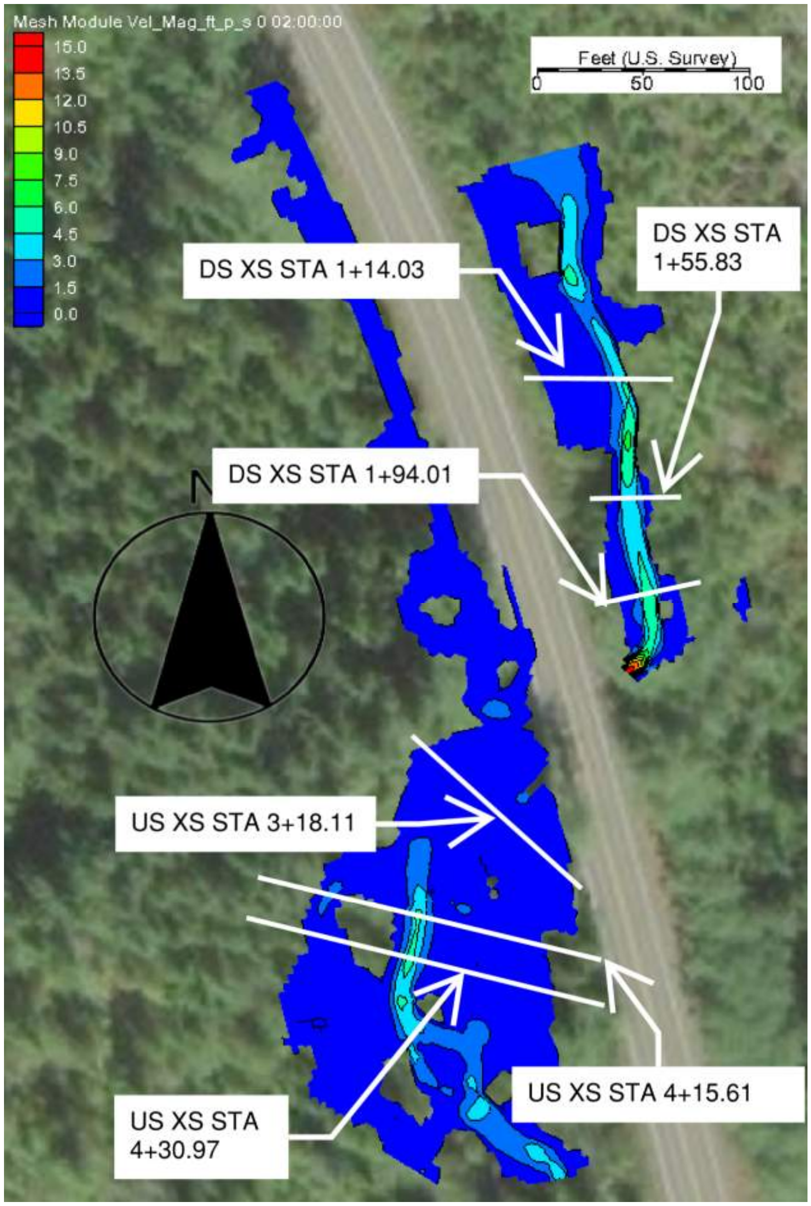


Figure 62~~6260~~: Existing-conditions 100-year velocity map with cross-section locations

Table 11: Existing-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main C~~c~~h.	ROB [a]
1+14.03	0.7	5.7	2.0
1+55.83	1.2	3.8	1.1
1+94.01	1.4	4.8	0.9
2+65.97	NA	9.5	NA
3+18.11	0.4	1.0	0.2
4+15.61	0.8	4.1	1.0
4+30.97	0.5	3.7	0.8

a. ROB/LOB locations were approximated at the tops of banks from inspecting the surface and 2-year top width.

4.3 Natural-Conditions Model Results

Natural-conditions hydraulic results for the main channel are summarized for the upstream and downstream cross sections as well as the cross section within the proposed crossing in Table 12~~Table 10~~. To create the natural conditions run, the road prism was removed beyond the wetted extents of the channel (approximately 50 feet of road were removed for this site), and the reference reach channel cross section was extended through the area otherwise occupied by the structure. Under natural conditions, the crossing does not backwater or overtop the smaller unnamed roadway heading west off of U.S. 101. However, flow is still spread across the floodplain in the upstream, unconfined channel because of accessible floodplains and log jams that cause the channel to spread. The WSELs for the range of flows simulated are shown in Figure 61~~Figure 60~~. The 2080 predicted 100-year flow WSEL is nearly equal to the 500-year flow.

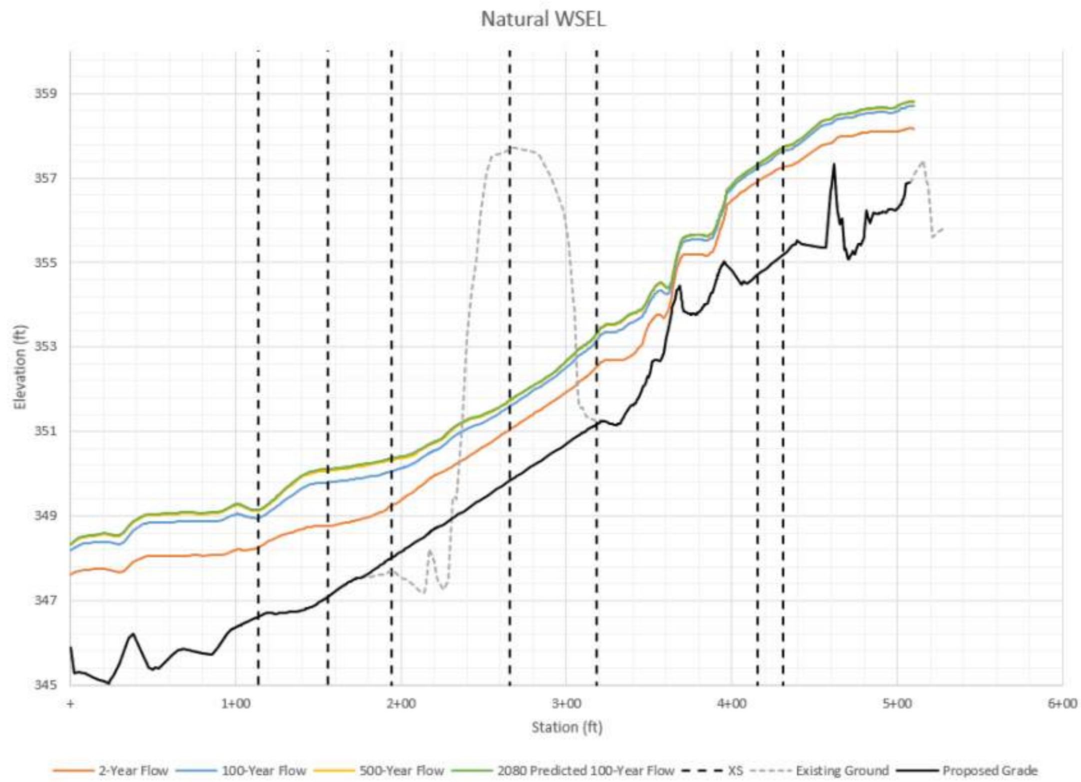
Upstream depths are similar to those in the downstream reach. The upstream depths range from 1.~~4~~5 to 2.~~6~~6 feet in upstream cross sections, while downstream depths range from 1.3~~1.2~~ to 3.~~0~~0 feet. Depths are 1.~~2~~4 to 2.2~~1.9~~ feet through the removed road embankment. Velocities ~~are also similar – they~~ range from ~~2.6~~2.9 to 4.9~~5.2~~ ft/s in the upstream reach, and from ~~3.0~~3.1 to 6.~~1~~2 ft/s in the downstream reach. The velocity is ~~4.4~~3.6 to ~~6.4~~4.8 ft/s through the space the culvert previously occupied. The similarities in velocity are easily explained by looking at the cross-section shapes and slopes; while the slope is approximately 2.2~~3~~ percent upstream, flow also spreads farther out across floodplains. Downstream, the slope is roughly 1.5 percent, but flow is confined mostly to the channel and occasional accessible floodplains. ~~Velocity through the cross section where the culvert was previously located is highest because the channel is confined entrenched through this section, and the slope is steep — close to 3 percent.~~ Shear values range from ~~0.6~~0.9 to ~~2.1~~2.0 lb/SF in the ~~downstream~~ upstream cross sections, and 0.~~7~~5 to 2.~~0~~4 lb/SF in the ~~upstream~~ downstream cross sections. Shear in the former culvert cross section ranged from 1.3 to ~~2.1~~1.9 lb/SF. When looking at the entire model domain, the largest velocities ~~occurr~~occur~~s~~ed ~~inside the former culvert stretch, and also at two locations~~ upstream where flow enters pools around log jams. Average velocities across the main channel, LOB, and ROB of each cross section for the 100-year flow are in Table 13~~Table 11~~. A velocity map showing the 100-year flow is in Figure 64~~Figure 63~~.

Typical cross sections for downstream and upstream are found in Figure 62~~Figure 61~~ and Figure 63~~Figure 62~~, respectively. The downstream cross section shows a channel that, while confined, has an accessible floodplain. The upstream cross section shows an unconfined channel spreading flow into the floodplains at low flows. All cross sections are provided in Appendix C.

Table 12: Hydraulic results for natural conditions within main channel

Hydraulic parameter	Cross-section (STA)	2-year	100-year	2080 predicted 100-year	500-year
Average water surface elevation (ft)	1+14.03	348.3~~348.3~~	349.0~~349.0~~	349.2~~349.2~~	349.1~~349.1~~
	1+55.82	348.8~~348.8~~	349.8~~349.8~~	350.1~~350.1~~	350.0~~350.1~~
	1+94.01	349.8~~349.2~~	350.4~~350.1~~	350.6~~350.4~~	350.6~~350.3~~
	2+65.97 [a]	351.3~~351.1~~	351.9~~351.6~~	352.1~~351.8~~	352.1~~351.7~~
	3+18.11	352.4~~352.6~~	353.0~~353.2~~	353.2~~353.4~~	353.2~~353.3~~
	4+15.61	356.9~~356.9~~	357.3~~357.2~~	357.3~~357.3~~	357.3~~357.3~~
	4+30.97	357.2~~357.3~~	357.6~~357.6~~	357.7~~357.7~~	357.7~~357.7~~
Maximum water depth (ft)	1+14.03	1.7~~1.7~~	2.4~~2.4~~	2.6~~2.6~~	2.6~~2.6~~
	1+55.82	1.7~~1.7~~	2.7~~2.7~~	3.0~~3.0~~	3.0~~3.0~~
	1+94.01	1.3~~1.2~~	1.9~~2.1~~	2.1~~2.4~~	2.1~~2.3~~
	2+65.97 [a]	1.4~~1.2~~	2.0~~1.8~~	2.2~~1.9~~	2.1~~1.9~~
	3+18.11	1.5~~1.4~~	2.1~~2.0~~	2.2~~2.2~~	2.2~~2.2~~
	4+15.61	2.3~~2.2~~	2.6~~2.5~~	2.6~~2.6~~	2.6~~2.6~~
	4+30.97	2.1~~2.1~~	2.4~~2.5~~	2.5~~2.6~~	2.5~~2.5~~
Average velocity magnitude (ft/s)	1+14.03	4.2~~4.1~~	5.7~~5.7~~	6.1~~6.2~~	6.1~~6.1~~
	1+55.82	3.1~~3.0~~	3.9~~3.8~~	4.1~~3.9~~	4.1~~3.9~~
	1+94.01	4.1~~4.4~~	5.2~~4.9~~	5.3~~4.8~~	5.3~~4.8~~
	2+65.97 [a]	3.6~~4.4~~	4.6~~6.1~~	4.8~~6.4~~	4.8~~6.4~~
	3+18.11	3.6~~3.6~~	4.6~~4.8~~	4.9~~5.2~~	4.9~~5.1~~
	4+15.61	3.3~~3.3~~	4.1~~4.1~~	4.3~~4.3~~	4.2~~4.2~~
	4+30.97	2.9~~2.6~~	3.9~~3.7~~	4.1~~3.9~~	4.1~~3.9~~
Average shear stress (lb/SF)	1+14.03	1.0~~1.0~~	1.6~~1.6~~	1.8~~1.8~~	1.8~~1.8~~
	1+55.82	0.5~~0.6~~	0.7~~0.6~~	0.7~~0.7~~	0.7~~0.7~~
	1+94.01	1.7~~1.3~~	2.4~~1.2~~	2.4~~1.1~~	2.4~~1.1~~
	2+65.97 [a]	1.3~~1.3~~	1.8~~1.9~~	1.9~~2.1~~	1.9~~2.0~~
	3+18.11	1.3~~0.7~~	1.8~~1.2~~	2.0~~1.3~~	2.0~~1.3~~
	4+15.61	1.3~~1.3~~	1.8~~1.9~~	1.9~~2.0~~	1.9~~2.0~~
	4+30.97	0.9~~0.9~~	1.4~~1.3~~	1.5~~1.4~~	1.5~~1.4~~

a. Cross section located at removed roadway embankment.



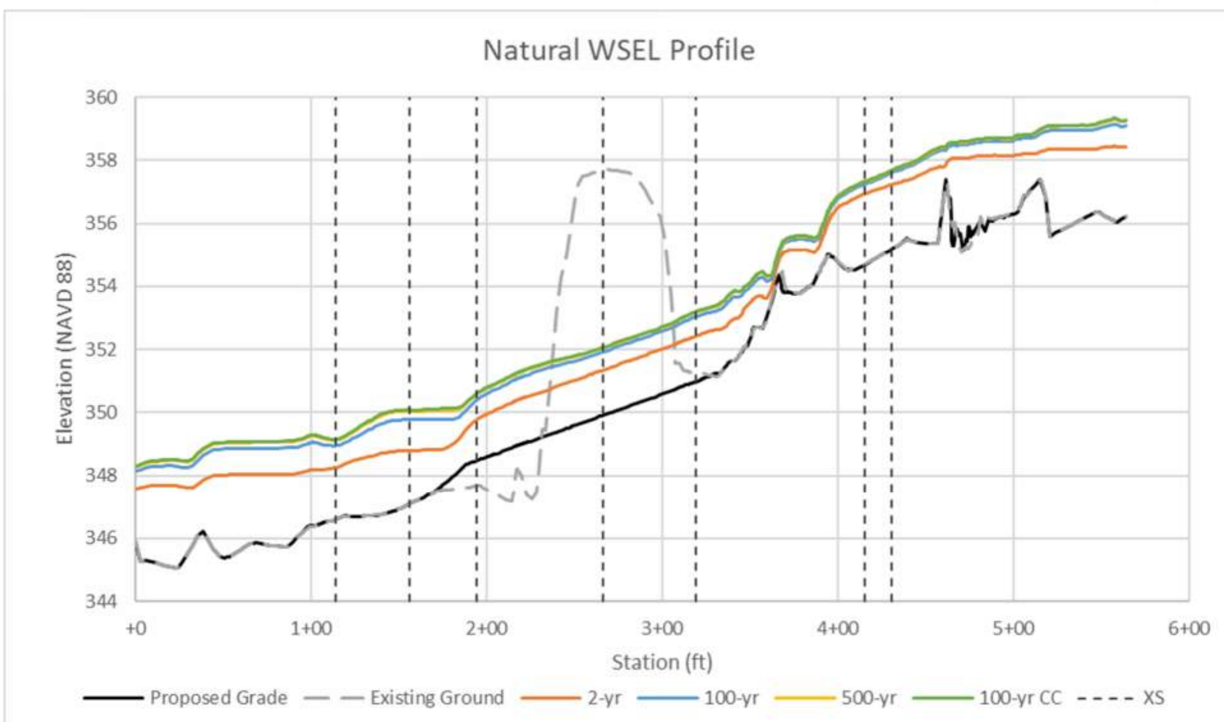


Figure 636361: Natural-conditions water surface profiles

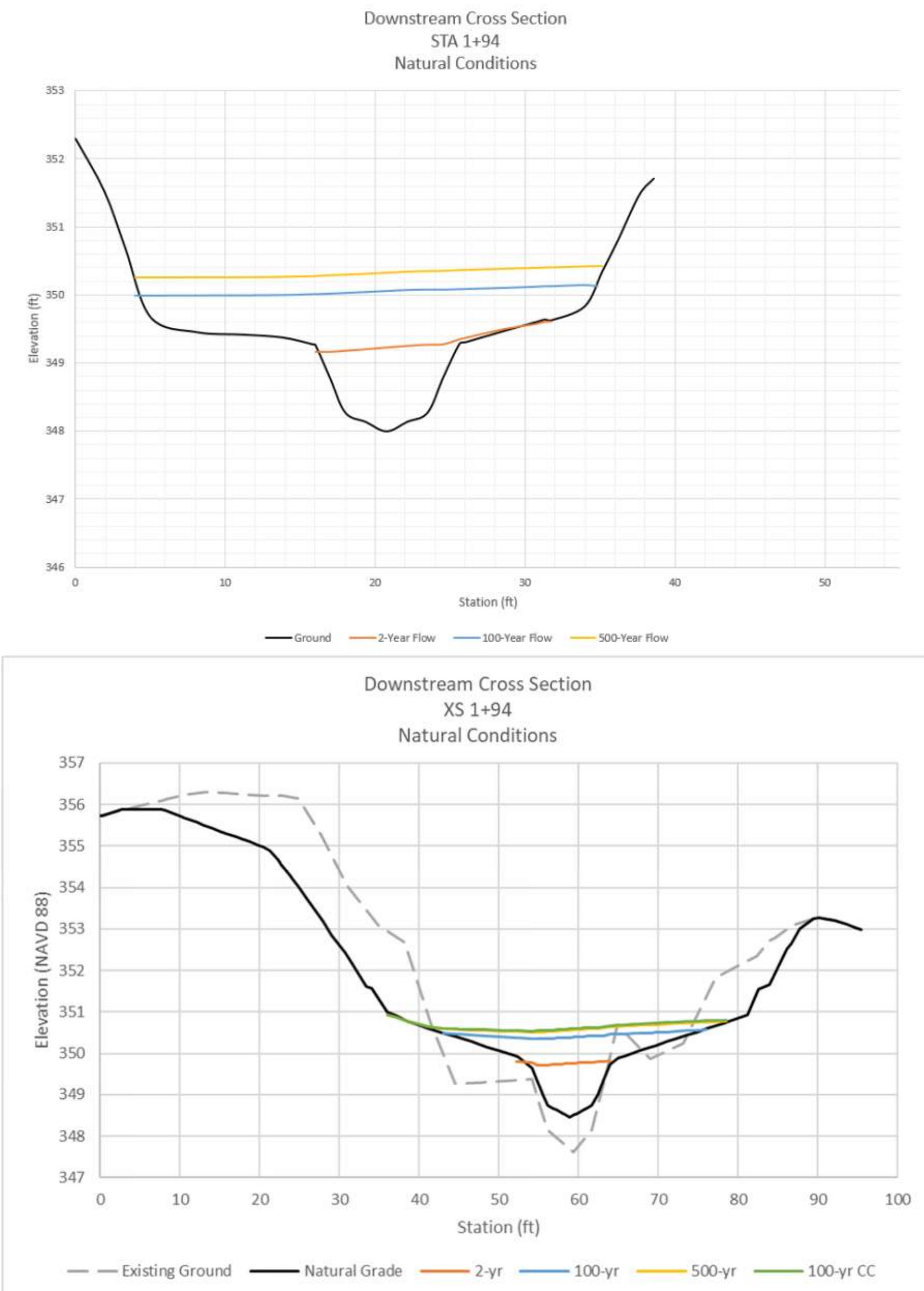


Figure 64~~6462~~: Typical downstream natural-conditions channel cross section (STA 1+94)

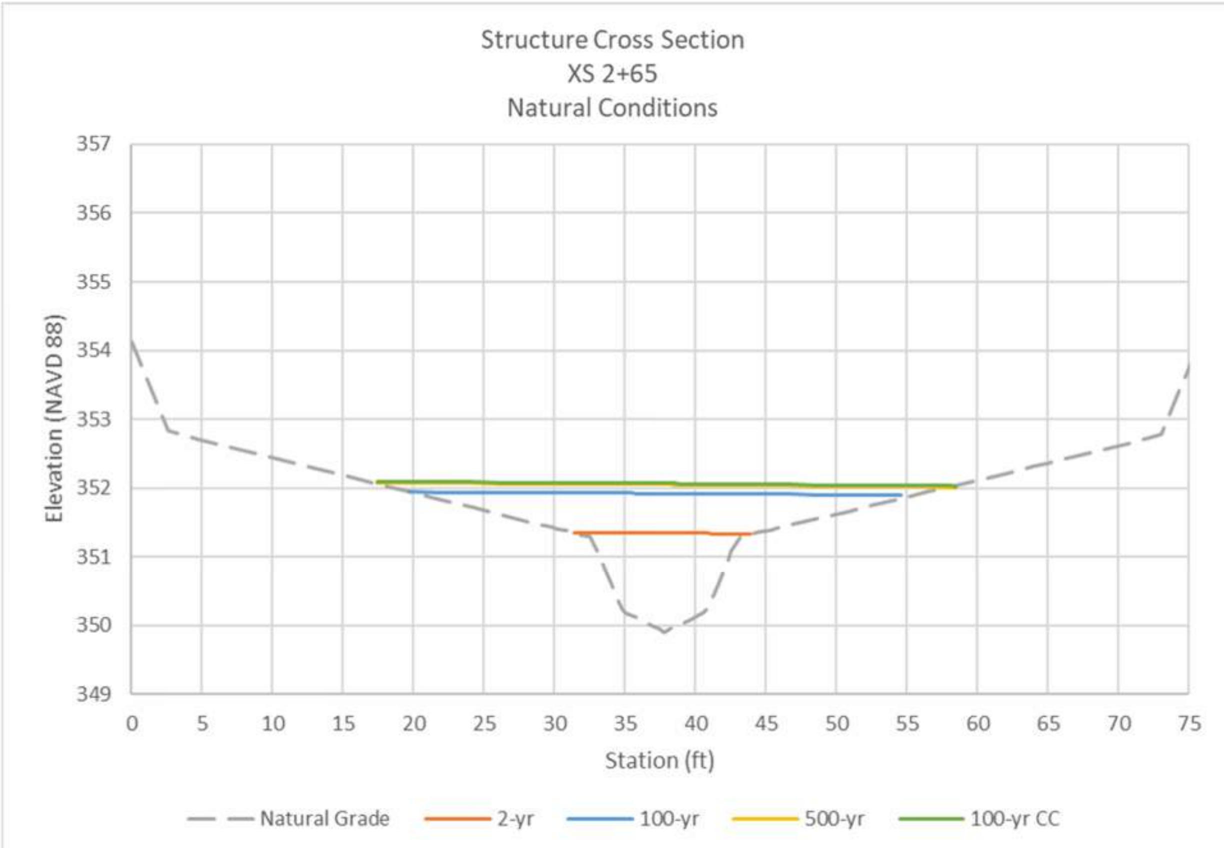
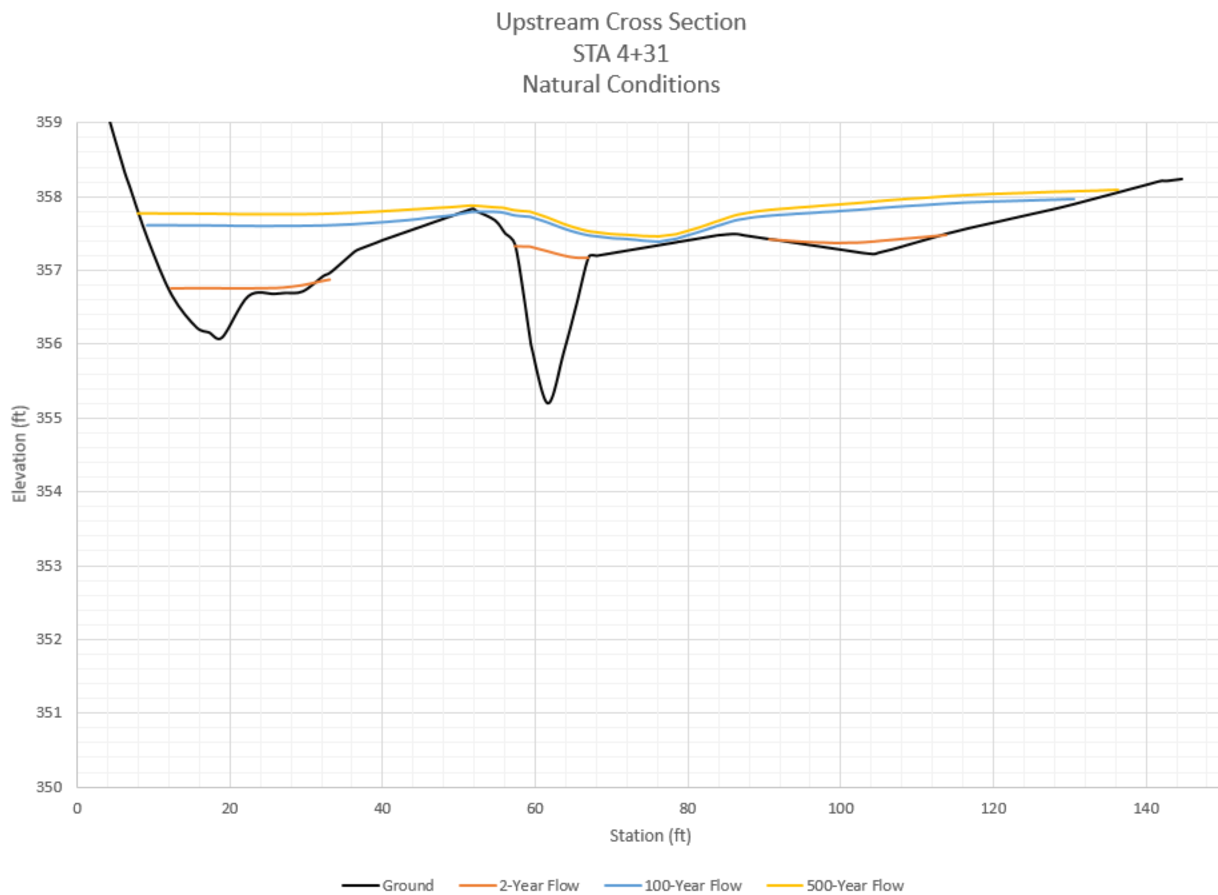


Figure 65: Cross section (STA 2+65) through removed structure for natural -conditions



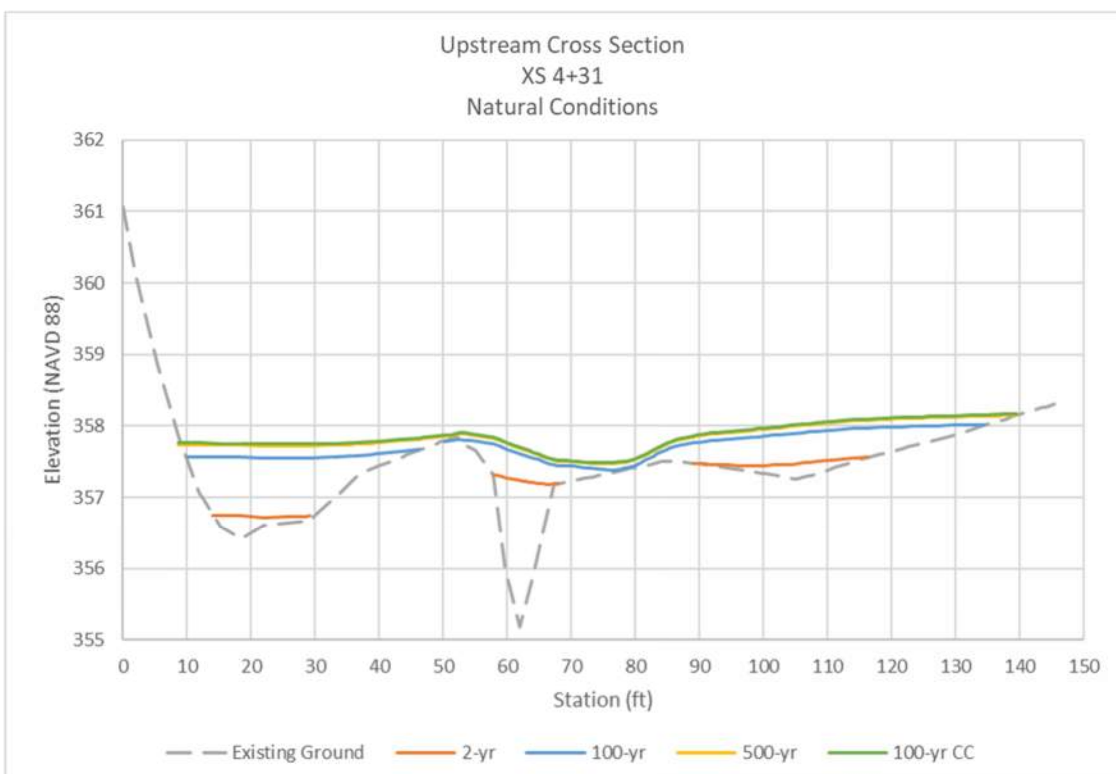
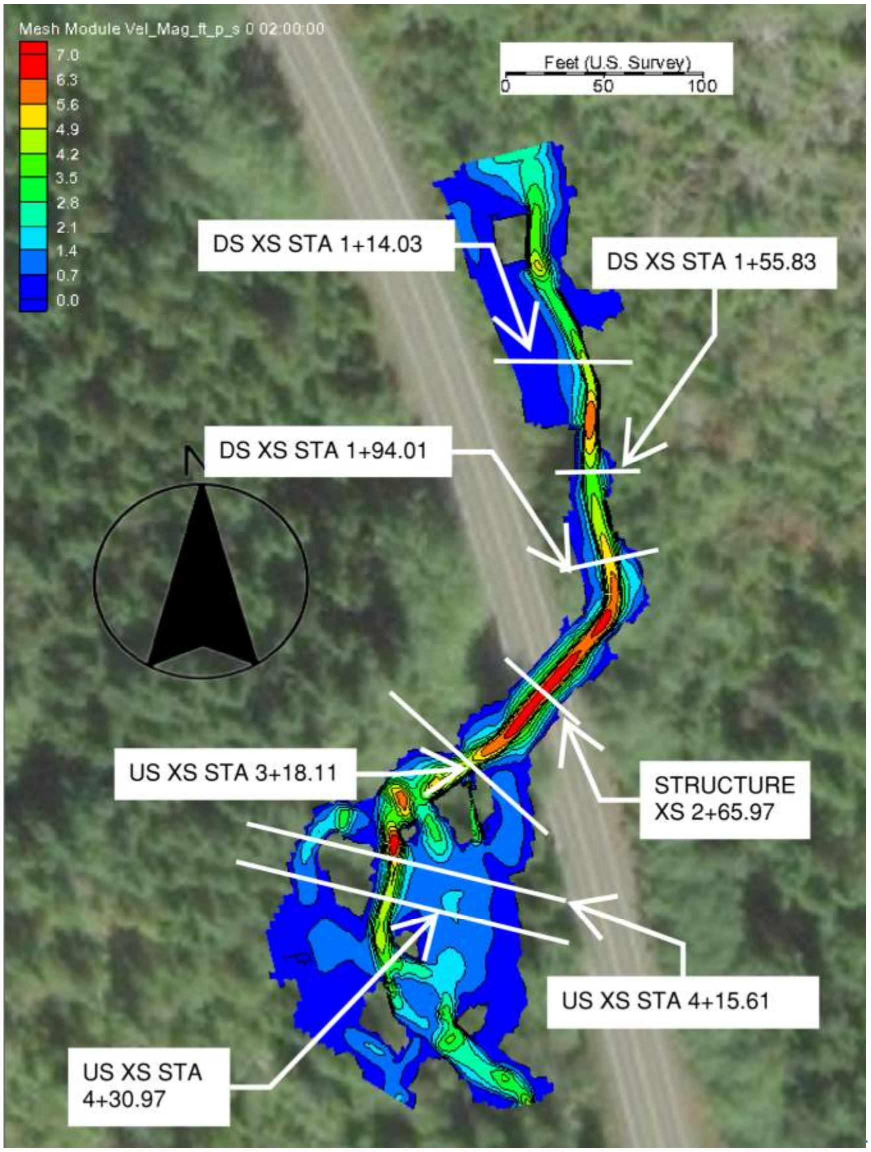


Figure 666~~663~~: Typical upstream natural-conditions channel cross section (STA 4+31)


Mesh Module Vel_Mag_ft_p_s 0 02:00:00
7.0
6.3
5.6
4.9
4.2
3.5
2.8
2.1
1.4
0.7
0.0
Feet (U.S. Survey)
0
50
100
N
DS XS STA 1+14.03
DS XS STA 1+55.83
DS XS STA 1+94.01
US XS STA 3+18.11
STRUCTURE
XS 2+65.97
US XS STA 4+15.61
US XS STA
4+30.97

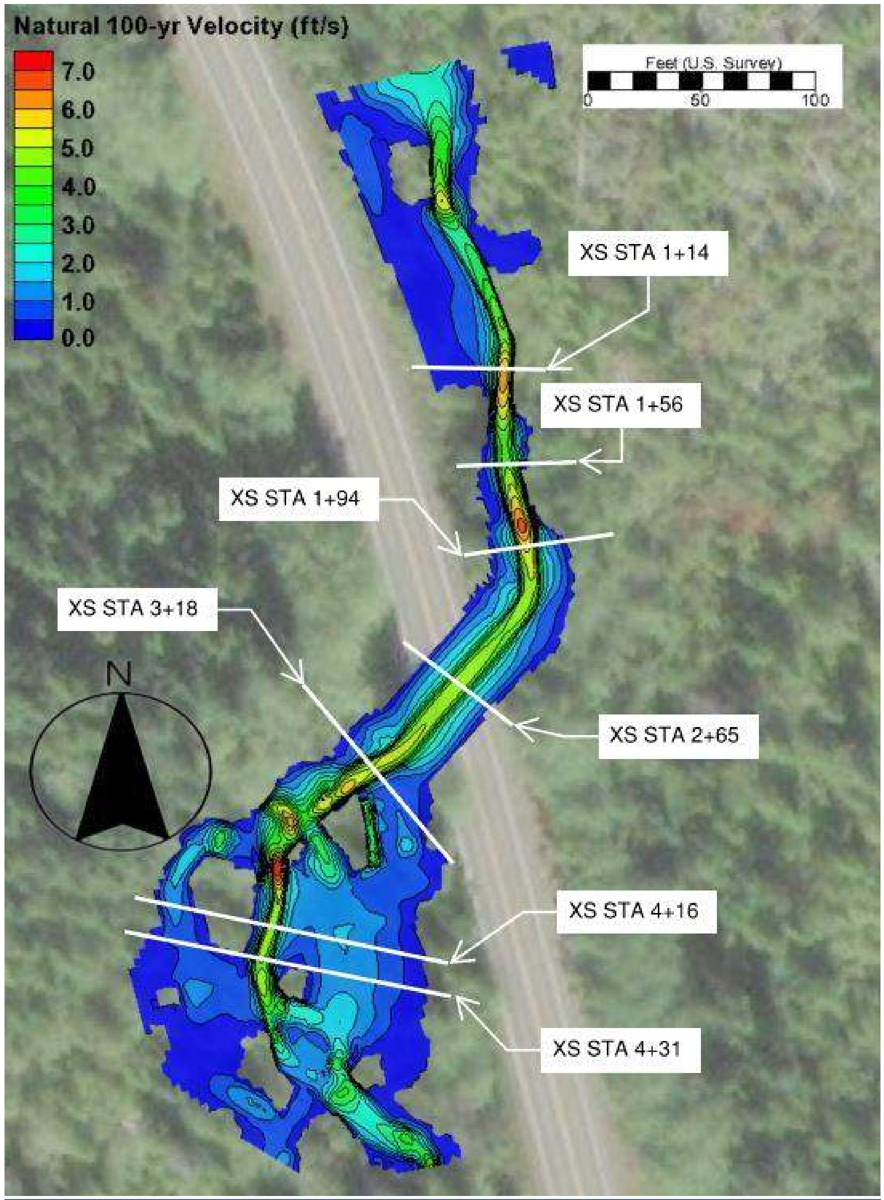


Figure 67~~67~~64: Natural-conditions 100-year velocity map with cross-section locations

Table 13: Natural-conditions velocities including floodplains at select cross sections

Location	Q100 Average Velocities (ft/s)		
	LOB [a]	Main Ch.	ROB [a]
1+14.03	0.7~~0.7~~	5.7~~5.7~~	1.9~~2.0~~
1+55.83	1.2~~1.2~~	3.9~~3.8~~	1.0~~1.2~~
1+94.01	1.4~~1.3~~	5.2~~4.9~~	1.2~~1.4~~
2+65.97 [b]	1.7~~2.2~~	4.6~~6.1~~	1.8~~2.3~~
3+18.11	1.2~~1.4~~	4.6~~4.8~~	0.8~~0.9~~
4+15.61	0.8~~0.8~~	4.1~~4.1~~	1.0~~1.0~~
4+30.97	0.5~~0.5~~	3.9~~3.7~~	0.8~~0.8~~

a. ROB/LOB locations were approximated at the tops of banks from inspecting the surface and 2-year top width.

b. Cross section located at removed roadway embankment.

4.4 Channel Design

Channel design for proposed conditions includes the floodplain utilization ratio (FUR), channel planform, shape, alignment, and gradient.

4.4.1 Floodplain Utilization Ratio

The FUR is defined as the flood-prone width (FPW) divided by the BFW. FPW is the water surface width at twice the bankfull depth, or the width at the 50-year to 100-year flood. A ratio under 3.0 is considered a confined channel and above 3.0 is considered an unconfined channel. When removing the culvert backwater influence by performing a model run simulation with a 20-foot-diameter culvert, the FPW upstream of the culvert inlet was measured three times, and the FPW downstream was measured twice. These values are identified below in Table 14~~Table 12~~, and the locations where they were measured are shown in Figure 65~~Figure 64~~.

Using a BFW of 10.3 feet, these FPWs result in an average FUR of 7.9, denoting this channel as unconfined.

Table 14: Flood-prone widths and floodplain utilization ratio results

Parameter	Measurements (ft)					
	Downstream		Upstream			Average
	1	2	3	4	5	-
FPW (measured from 100-year top width of model)	44	21	104	126	113	81.6
Associated FUR	4.3	2.0	10.1	12.2	11.0	7.9
Average FUR (upstream and downstream)	**3.2**		**11.1**			

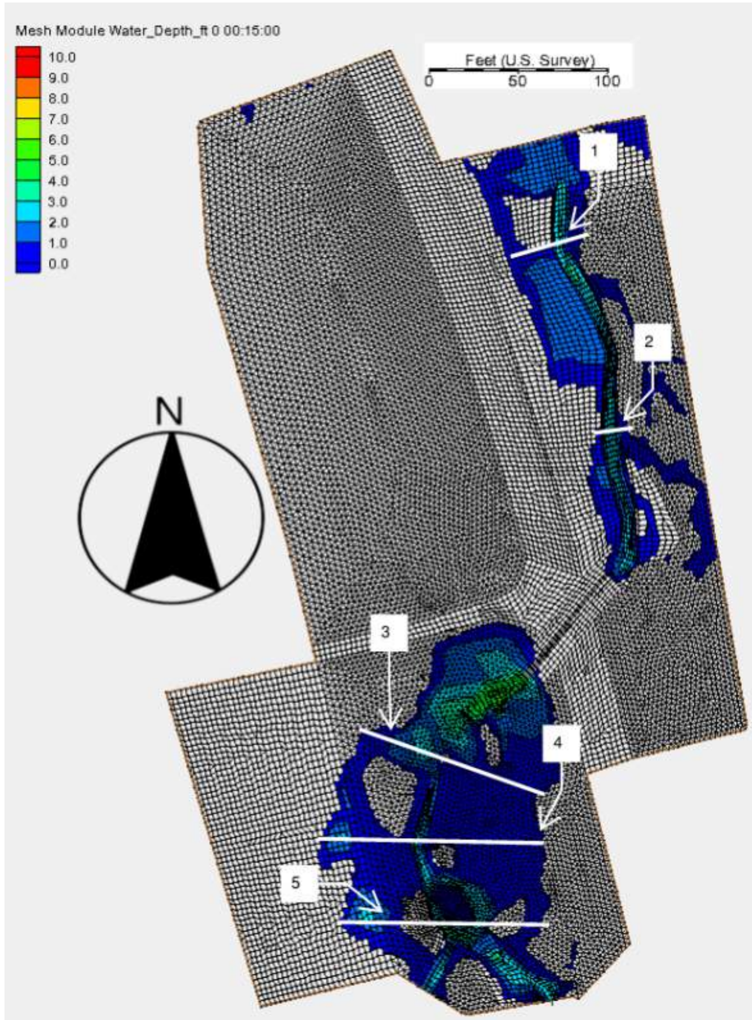


Figure 68~~6865~~: Locations of FPW measurements

4.4.2 Channel Planform and Shape

The WCDG requires that the channel planform and shape mimic conditions within a reference reach. The proposed channel shape includes 10 horizontal (H):1 vertical (V) slopes between the centerline and bank toe and 2H:1V bank slopes to create a channel similar to the reference channel shape. Floodplain slopes at 16H:1V simulate the reference floodplains and channel benches, thereby connecting the proposed grading to the existing surface. This is shown in Figure 66~~Figure 65~~.

The identified reference reach was chosen downstream of the culvert because the upstream reach is populated with log jams and the stream channel does not display natural conditions, as explained earlier in this PHD Report. The design channel shape is based on the reference reach shape. In Figure 67~~Figure 69Figure 66~~, the reference channel shape is shown as a brown dashed line and is located at STA 1+88.98, which is inside the reference reach identified in Section 2.8.1. The design channel shape is shown in solid green. The proposed grading was evaluated in SMS. The natural-conditions model was used to view the 2-year flow depth to confirm that the flow was approximately at the top of banks of the proposed grading. Also, the top widths for all flow events at the reference reach were compared to the top widths at the proposed structure. Channel benches are activated at flows as low as the 2-year event upstream and at several locations downstream as well. The top widths of the reference reach and proposed structure location were similar, demonstrating that the proposed grading accurately reflects the channel shape of the reference reach.

This channel does not show the integration of LWM into the bed or within the channel banks, which will be a critical feature to support reduction of the downstream channel gradient and increase to hydraulic roughness to maintain a lower gradient reach with sufficiently low velocities to reduce grain size and support pool-riffle morphology. Those details will be ~~elucidated~~determined in the FHD.

~~Because the design channel shape matches closely, t~~The channel design cross-section is expected to ~~shape~~ respond over time to ~~closely~~ mimic the existing ~~channel~~shape, namely the lowering of the thalweg. The channel is expected to maintain its overall ~~shape, but~~general shape but will adjust to form channel features such as low-flow meanders ~~or~~ and pools from large woody material (LWM)~~ deposits from natural processes~~.

A low-flow channel will be added in during the Final Hydraulic Design~~later~~ stage~~s~~ of the project that connects habitat features together so that the project is not a low-flow barrier. The low-flow channel will be placed as directed by the engineer in the field.

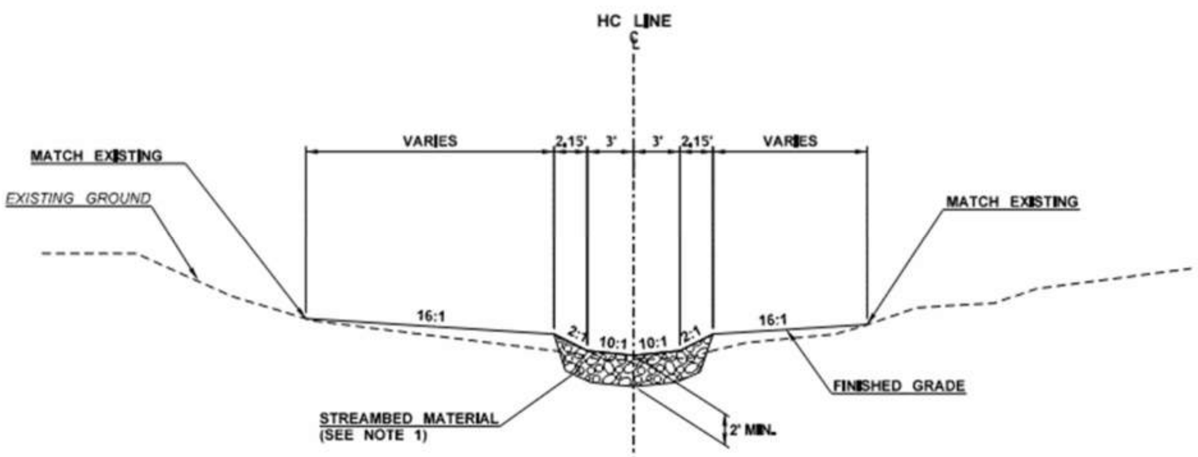


Figure 69~~6966~~: Design cross section

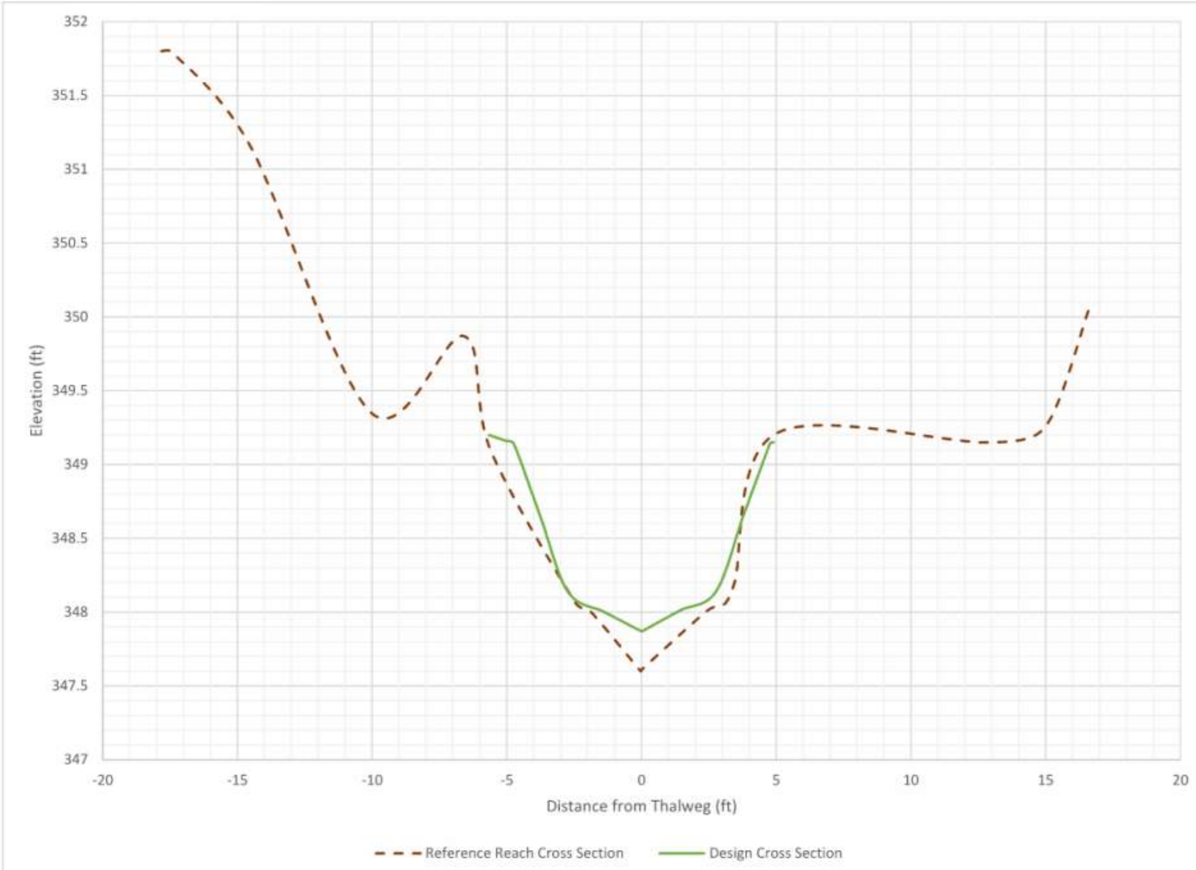


Figure 70~~7067~~: Proposed versus existing cross section

4.4.3 Channel Alignment

The proposed project alignment follows the existing alignment. The project will include channel grading approximately ~~60~~ 175 feet downstream of the channel outlet to roughly ~~15~~ 25 feet upstream of the channel inlet. The channel alignment was constrained on the upstream side because of a large log jam surveyed. ~~In the field, it was observed that this~~Field observations indicate that the existing log jam, composed of wood recruited from historical logging activities, ~~acts as a dam and~~ obstructs flow during flood events, redirects water to accessible floodplain surfaces, and retains fine sediments in the upstream reach.~~; it is made up of wood recruited from past logging activities.~~ The proposed grading limit ~~was~~ ends~~ed~~ prior to this log jam so that it ~~would~~ is not ~~be impacted~~disturbed.

Lengthening the radius of curvature in the channel bend downstream of the culvert was considered, but hydraulic model results do not indicate a high risk of local erosion on the right bank compared to existing conditions. At the 2-year event, modeled velocity is relatively uniform in the downstream reach under proposed conditions. Therefore, realigning the downstream reach would not provide a significant benefit to habitat and hydraulic complexity.

4.4.4 Channel Gradient

The WCDG recommends that the proposed structure bed gradient not be more than 25 percent steeper than the existing stream gradient upstream of the crossing (WCDG Equation 3.1). The proposed channel gradient is 2.~~6~~ 0 percent~~ and the immediate upstream channel gradient is approximately 4.9 percent, resulting in a structure slope that is shallower than the upstream slope~~. ~~However, t~~The average upstream slope over ~~a distance of approximately~~approximately 2,000 feet ~~based on~~of LiDAR data is ~~roughly~~ 2.2 percent. ~~Using this upstream slope results in a~~The corresponding slope ratio ~~of~~ is ~~1.2~~0.9, which is within the recommended WCDG limits.~~ It is noted that the immediate upstream gradient is approximately 4.9 percent, which results in a structure slope that is shallower than the upstream slope if only this short distance is considered. Since the 4.9 percent grade of the approach segment is likely driven by local downcutting and entrenchment of the channel bed from the undersized culvert, it is appropriate to consider the average upstream gradient to derive the slope ratio.~~

As discussed in Section 2.8, due to the known disparity in slope between the reference reach and the design reach, the slope ratio comparison was based on the slope of the upstream reach, 2.2%, resulting in a slope ratio of 0.90 (Figure 39 above). ~~Comparison of the design slope of 2.6 percent to the reference reach slope of 1.5 percent indicates that the 1.25 slope ratio is exceeded. To meet~~T~~ t~~he reference reach slope (1.5 percent) ~~ratio~~would be too flat for~~,~~ the grading ~~would need to reach approximately 300 feet upstream of the existing culvert and would grade through~~~~necessitate disturbing~~ several ~~stable~~ ~~log jams~~to connect upstream. The Draft PHD proposed a slope of 2.6 percent to minimize grading outside of the existing structure footprint, but this was too steep for the reach and did not meet stream simulation criteria. ~~It was deemed most appropriate~~We propose to grade the structure at a 2.0~~6~~ percent slope, which is an intermediate value between the surveyed upstream and downstream slopes. This involves extending the grading approximately 175 feet downstream of the crossing and provides an opportunity to improve habitat conditions in the degraded downstream reach by re-meandering the channel and placing 6 to 8 inches of fill in incised areas to improve floodplain connectivity. ~~The proposed 2.6 percent design slope compares well with the calculated longitudinal profile average upstream slope of 2.2 percent (Figure 39Figure 38 above). Some degradation may occur in the channel~~Channel response is ~~expected~~possible at the transition between the proposed design slope and the existing upstream gradient, which~~. This~~ is described in more detail in Section 8.2.

4.5 Design Methodology

The proposed fish passage design was developed using the 2013 *Water Crossing Design Guidelines* (Barnard et al. 2013) and the WSDOT *Hydraulics Manual* (WSDOT 2019). Using the guidance in these two documents, the unconfined bridge design method was determined to be the most appropriate at this crossing because the FUR was calculated to be greater than 3.0.

Two requirements for the stream simulation method were met: the BFW was less than 15 feet, and the proposed channel gradient meets the slope ratio. However, the FUR was calculated to be more than 3.0, which means the channel is unconfined and the unconfined bridge approach must be used to allow for ~~the~~ flow in the floodplains.

4.6 Future Conditions: Proposed 15-Foot Minimum Hydraulic Opening

The hydraulic opening is defined as the width perpendicular to the creek beneath the proposed structure that is necessary to convey the design flow and allow for natural geomorphic processes. The hydraulic opening assumes vertical walls at the edge of the minimum hydraulic opening width unless otherwise specified.

The starting point for the design of all WSDOT structures is Equation 3.2 of the WCDG, rounded up to the nearest whole foot. For this crossing, a minimum hydraulic opening of 15 feet was determined to be the minimum starting point based on a BFW of 10.3 feet determined from field measurements during the second site visit on June 25, 2021 ~~topographic survey and modeled 2-year flow widths outlined in Section 2.8.2~~ and confirmed with WSDOT topographic survey, modeled 2-year flow width, and WDFW climate-predicted BFW estimates described in Section 2.8.2~~bankfull measurements in the field~~.

Proposed-conditions hydraulic results are summarized for the upstream and downstream cross sections as well as the cross section within the proposed crossing in Table 15~~Table 13~~. A cross section showing WSEL in the proposed structure is shown in Figure 69~~Figure 68~~. The larger proposed structure reduced water surface elevations upstream and does not cause backwater (Figure 68~~Figure 67~~). The 2080 projected 100-year flow WSEL is nearly equal to the 500-year flow. The 100-year water surface elevation at the upstream cross section (STA 3+18) decreased by 3.5~~1~~ feet from existing conditions. Also, there is no overtopping of U.S. 101 or of the unnamed roadway heading west off of U.S. 101 under proposed conditions and all flow is conveyed through the proposed opening.

Upstream channel velocities vary from 2.~~7~~9 to 4.9~~8~~ ft/s, and the downstream proposed-conditions velocities vary from 3.~~0~~1 to 6.~~2~~1 ft/s. Velocities upstream and downstream have both increased slightly ~~compared to existing conditions~~under proposed conditions ~~because there is less backwater upstream, and more flow is entering the system downstream than during~~~~resulting from~~due to the increase in conveyance from existing conditions.

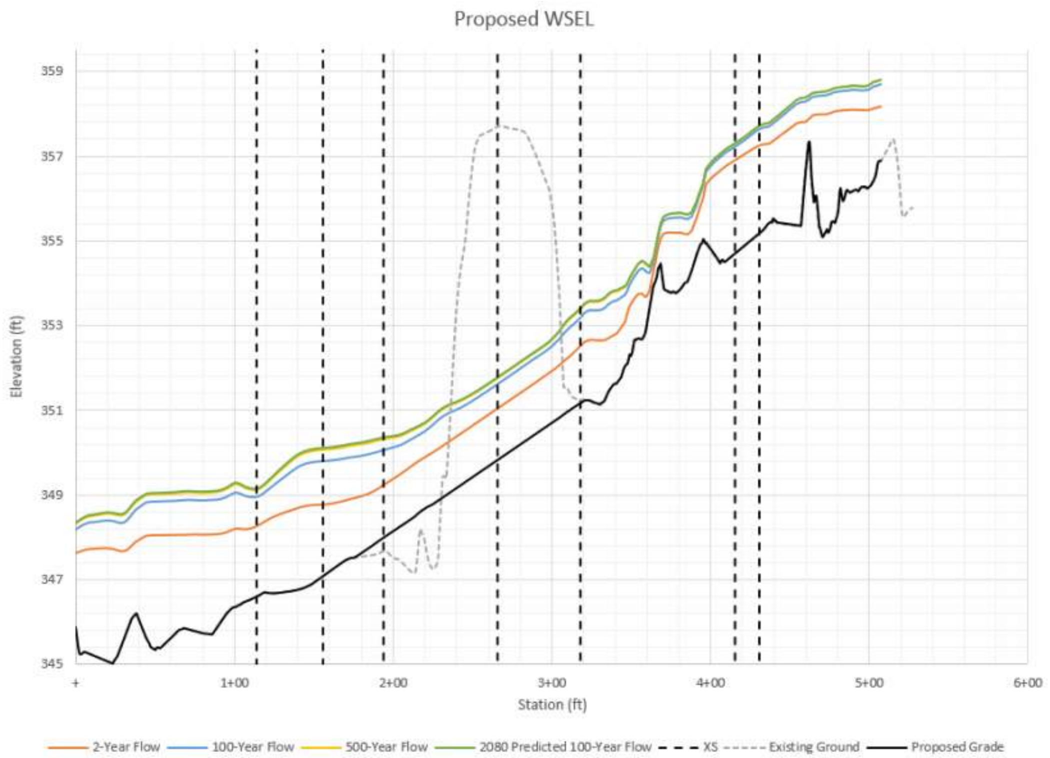
In upstream cross sections, shear stress increases slightly from existing conditions because of the removal of backwater at the culvert inlet~~. They~~ , where computed values vary from 0.~~7~~9 to 1.9~~2.0~~ lb/SF. ~~S~~Computed shear stresses in downstream cross sections remain close to shear stresse~~d~~s seen in ~~consistent with~~ existing conditions. ~~They~~ Values vary from 0.~~6~~5 to 2.4~~1.8~~ lb/SF. Average velocities across the main channel, LOB, and ROB of each cross section for the 100-year flow are summarized in Table 16~~Table 14~~. A velocity map showing the 100-year flow is in Figure 70~~Figure 69~~, and a second velocity map showing the 2080 predicted 100-year flow is in Figure 71~~Figure 70~~.

The proposed crossing structure decreases the change between the upstream and downstream shear stresses, depth, and velocities, ~~thus creating a more equilibrated reach~~thereby reducing the discontinuities in hydraulic conditions within the project reach ~~as a whole~~ (Figure 70~~Figure 69~~).

Table 15: Hydraulic results for proposed conditions within main channel

Hydraulic parameter	Cross section (STA)	2-year	100-year	2080 predicted 100-year	500-year
Average water surface elevation (ft)	1+14.03	348.3~~348.3~~	349.0~~349.0~~	349.2~~349.2~~	349.1~~349.1~~
	1+55.82	348.8~~348.8~~	349.8~~349.8~~	350.1~~350.1~~	350.0~~350.1~~
	1+94.01	349.8~~349.2~~	350.4~~350.1~~	350.6~~350.4~~	350.6~~350.3~~
	2+65.97 [a]	351.4~~351.1~~	352.1~~351.6~~	352.3~~351.8~~	352.2~~351.8~~
	3+18.11	352.5~~352.6~~	353.2~~353.2~~	353.4~~353.5~~	353.4~~353.4~~
	4+15.61	356.9~~356.9~~	357.3~~357.2~~	357.3~~357.3~~	357.3~~357.3~~
	4+30.97	357.2~~357.3~~	357.6~~357.6~~	357.7~~357.7~~	357.7~~357.7~~
Maximum water depth (ft)	1+14.03	1.7~~1.7~~	2.4~~2.4~~	2.6~~2.6~~	2.6~~2.6~~
	1+55.82	1.7~~1.7~~	2.7~~2.7~~	3.0~~3.0~~	3.0~~3.0~~
	1+94.01	1.3~~1.2~~	1.9~~2.1~~	2.1~~2.4~~	2.1~~2.3~~
	2+65.97 [a]	1.5~~1.2~~	2.1~~1.8~~	2.4~~2.0~~	2.3~~1.9~~
	3+18.11	1.5~~1.4~~	2.2~~2.0~~	2.5~~2.3~~	2.4~~2.2~~
	4+15.61	2.3~~2.2~~	2.6~~2.5~~	2.6~~2.6~~	2.6~~2.6~~
	4+30.97	2.1~~2.1~~	2.4~~2.5~~	2.5~~2.6~~	2.5~~2.5~~
Average velocity magnitude (ft/s)	1+14.03	4.2~~4.1~~	5.7~~5.7~~	6.1~~6.2~~	6.1~~6.1~~
	1+55.82	3.1~~3.0~~	3.9~~3.8~~	4.1~~3.9~~	4.1~~3.9~~
	1+94.01	4.0~~4.4~~	5.2~~4.9~~	5.4~~4.8~~	5.3~~4.8~~
	2+65.97 [a]	3.5~~4.4~~	4.8~~6.2~~	5.1~~6.7~~	5.1~~6.6~~
	3+18.11	3.4~~3.4~~	4.3~~4.6~~	4.5~~4.8~~	4.5~~4.8~~
	4+15.61	3.3~~3.3~~	4.1~~4.1~~	4.2~~4.3~~	4.2~~4.2~~
	4+30.97	2.9~~2.7~~	3.9~~3.7~~	4.1~~3.9~~	4.1~~3.9~~
Average shear stress (lb/SF)	1+14.03	1.0~~1.0~~	1.6~~1.6~~	1.8~~1.8~~	1.7~~1.8~~
	1+55.82	0.5~~0.6~~	0.7~~0.6~~	0.7~~0.7~~	0.7~~0.7~~
	1+94.01	1.7~~1.2~~	2.4~~1.2~~	2.4~~1.1~~	2.4~~1.1~~
	2+65.97 [a]	1.2~~1.3~~	1.9~~2.0~~	2.1~~2.2~~	2.1~~2.2~~
	3+18.11	1.1~~0.7~~	1.6~~1.0~~	1.6~~1.1~~	1.6~~1.1~~
	4+15.61	1.3~~1.3~~	1.8~~1.9~~	1.9~~2.0~~	1.9~~2.0~~
	4+30.97	0.9~~0.9~~	1.4~~1.3~~	1.5~~1.4~~	1.5~~1.4~~

a. Cross section located within proposed structure.



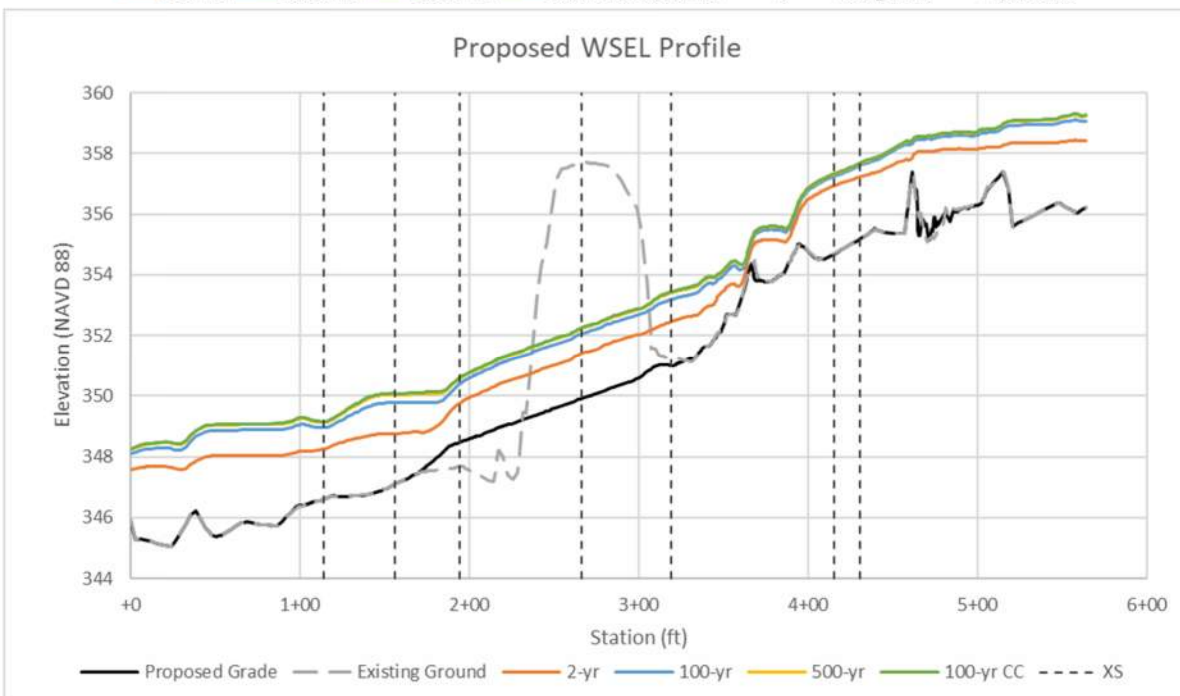
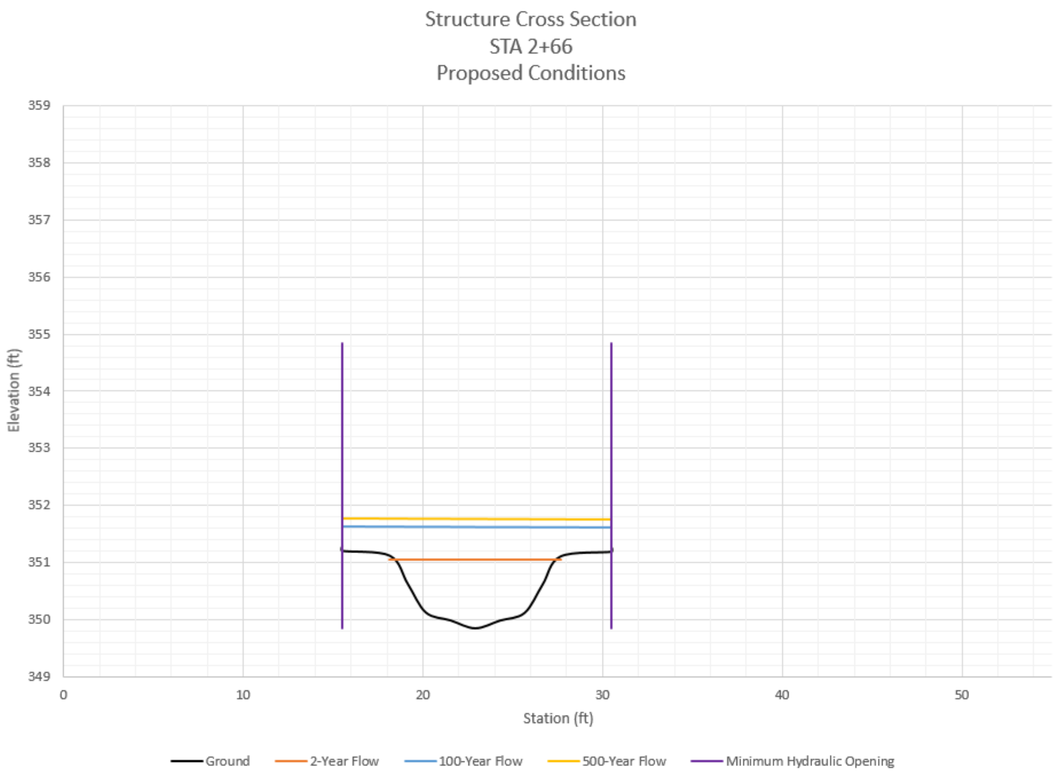


Figure 71~~7168~~: Proposed-conditions water surface profiles



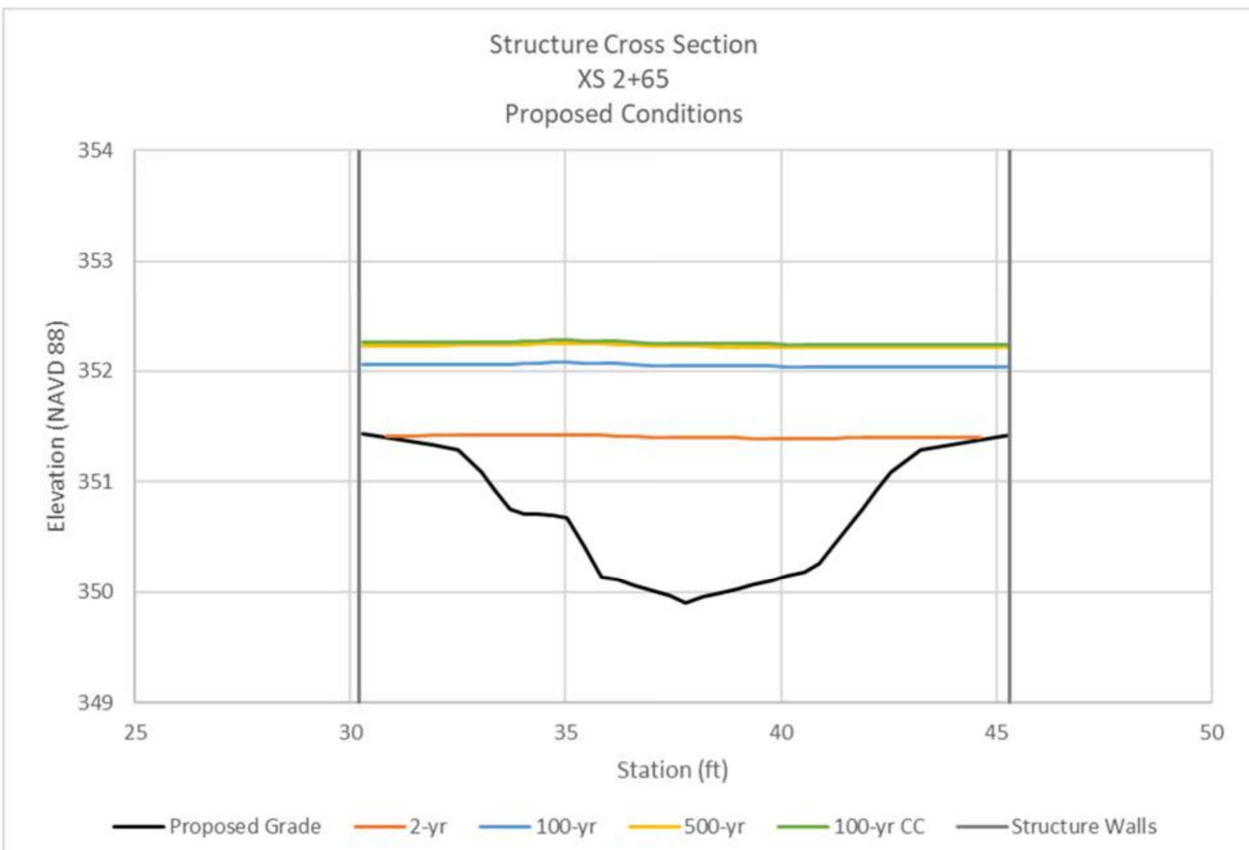
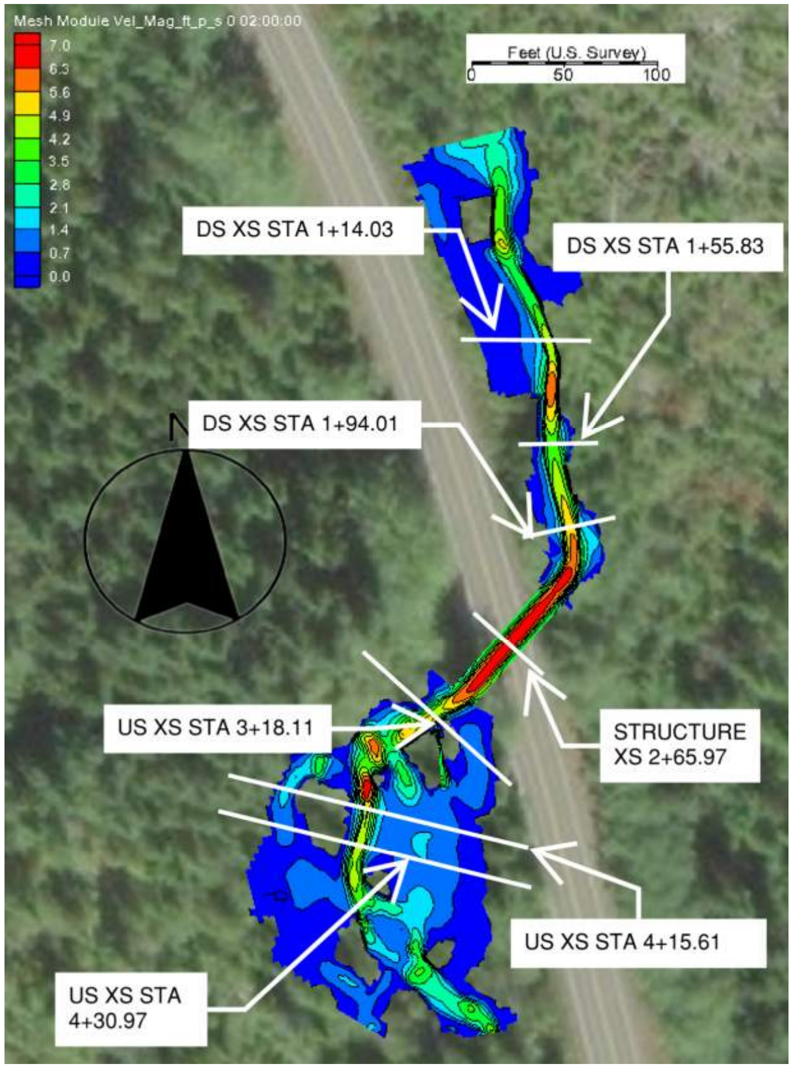


Figure 72~~7269~~: Section through proposed structure (STA 2+6~~6~~5)


Mesh Module Vel_Mag_ft_p_s 0 02:00:00
7.0
6.3
5.6
4.9
4.2
3.5
2.8
2.1
1.4
0.7
0.0
Feet (U.S. Survey)
0
50
100
N
DS XS STA 1+14.03
DS XS STA 1+55.83
DS XS STA 1+94.01
STRUCTURE XS 2+65.97
US XS STA 3+18.11
US XS STA 4+15.61
US XS STA 4+30.97

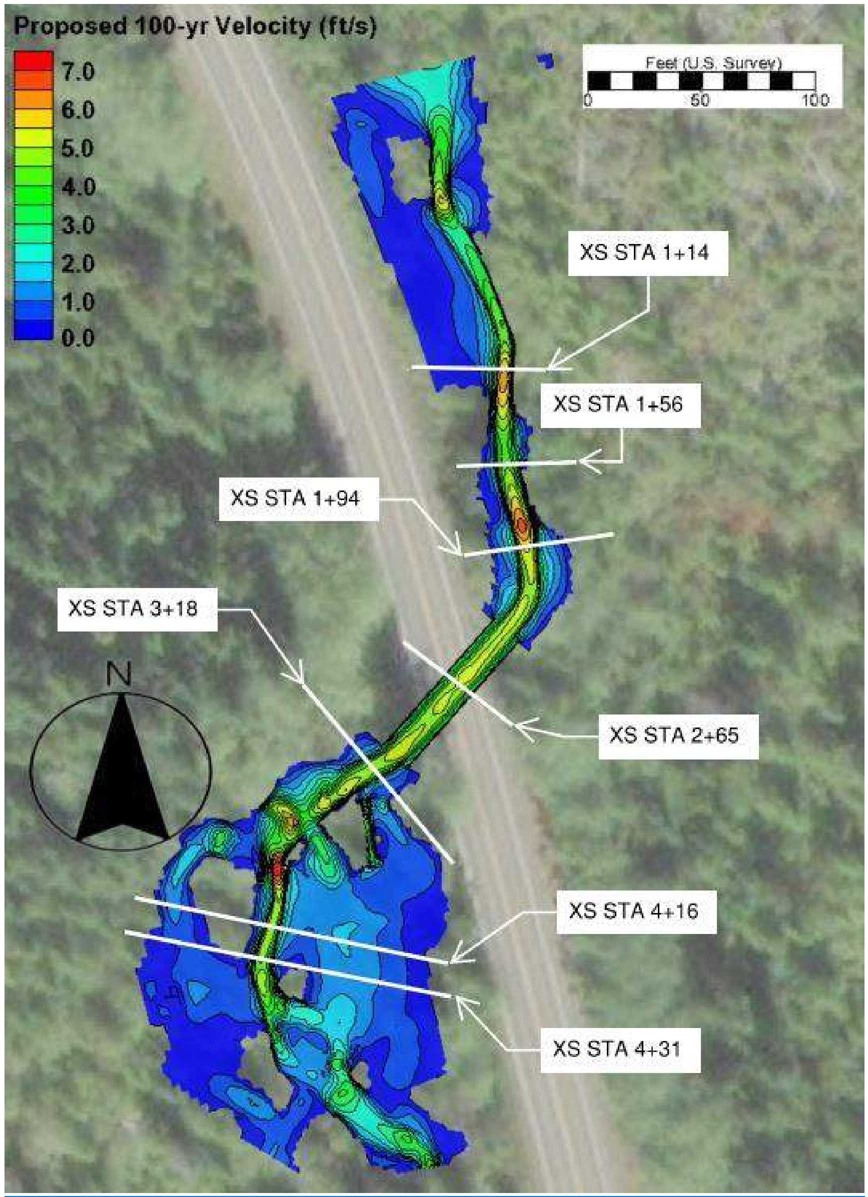


Figure 73~~7370~~: Proposed-conditions 100-year velocity map. Flow direction is from bottom to top of figure.

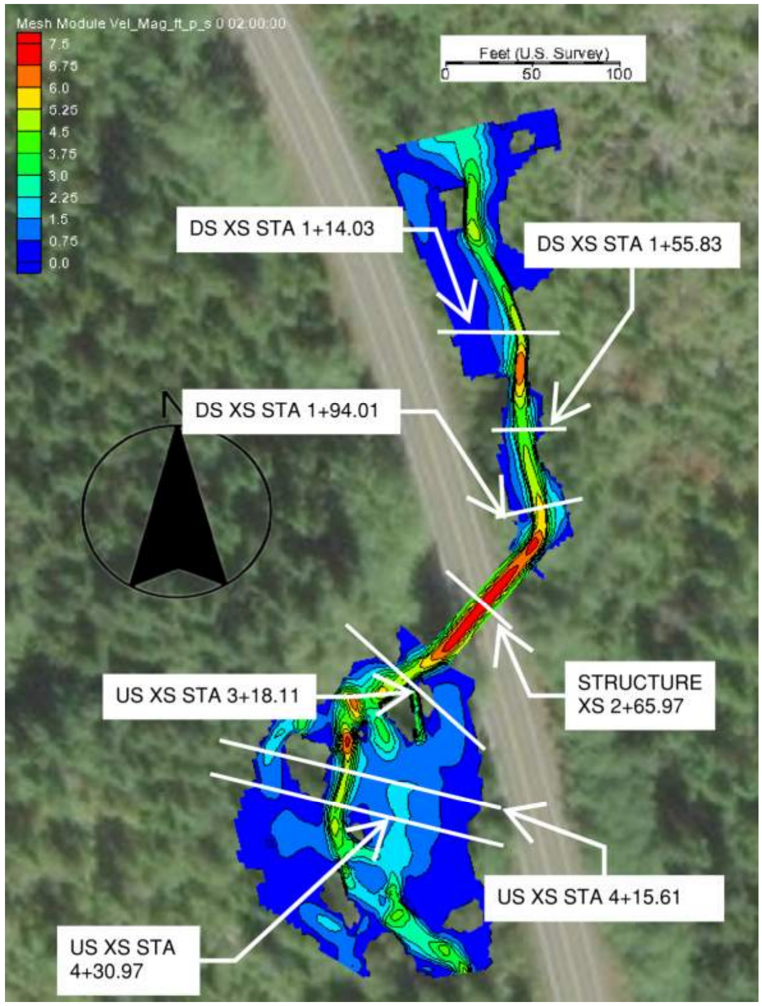
Table 16: Proposed-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	**Main ch.**	**ROB [a]**
1+14.03	0.7~~0.7~~	5.7~~5.7~~	1.9~~2.0~~
1+55.83	1.2~~1.2~~	3.9~~3.8~~	1.0~~1.2~~
1+94.01	1.5~~1.5~~	5.2~~4.9~~	1.2~~1.3~~
2+65.97 [b]	2.9~~3.6~~	4.8~~6.2~~	3.0~~3.8~~
3+18.11	1.5~~1.4~~	4.3~~4.6~~	0.9~~0.8~~
4+15.61	0.8~~0.8~~	4.1~~4.1~~	1.0~~1.0~~

4+30.97	0.5~~0.5~~	3.9~~3.7~~	0.8~~0.8~~

a. ROB/LOB locations were approximated at the tops of banks from inspecting the surface and 2-year top width.

b. Cross section located at proposed structure.


Mesh Module Vel_Mag_ft_p_s 0 02:00:00
7.5
6.75
6.0
5.25
4.5
3.75
3.0
2.25
1.5
0.75
0.0
Feet (U.S. Survey)
0
50
100
N
DS XS STA 1+14.03
DS XS STA 1+55.83
DS XS STA 1+94.01
STRUCTURE XS 2+65.97
US XS STA 3+18.11
US XS STA 4+15.61
US XS STA 4+30.97

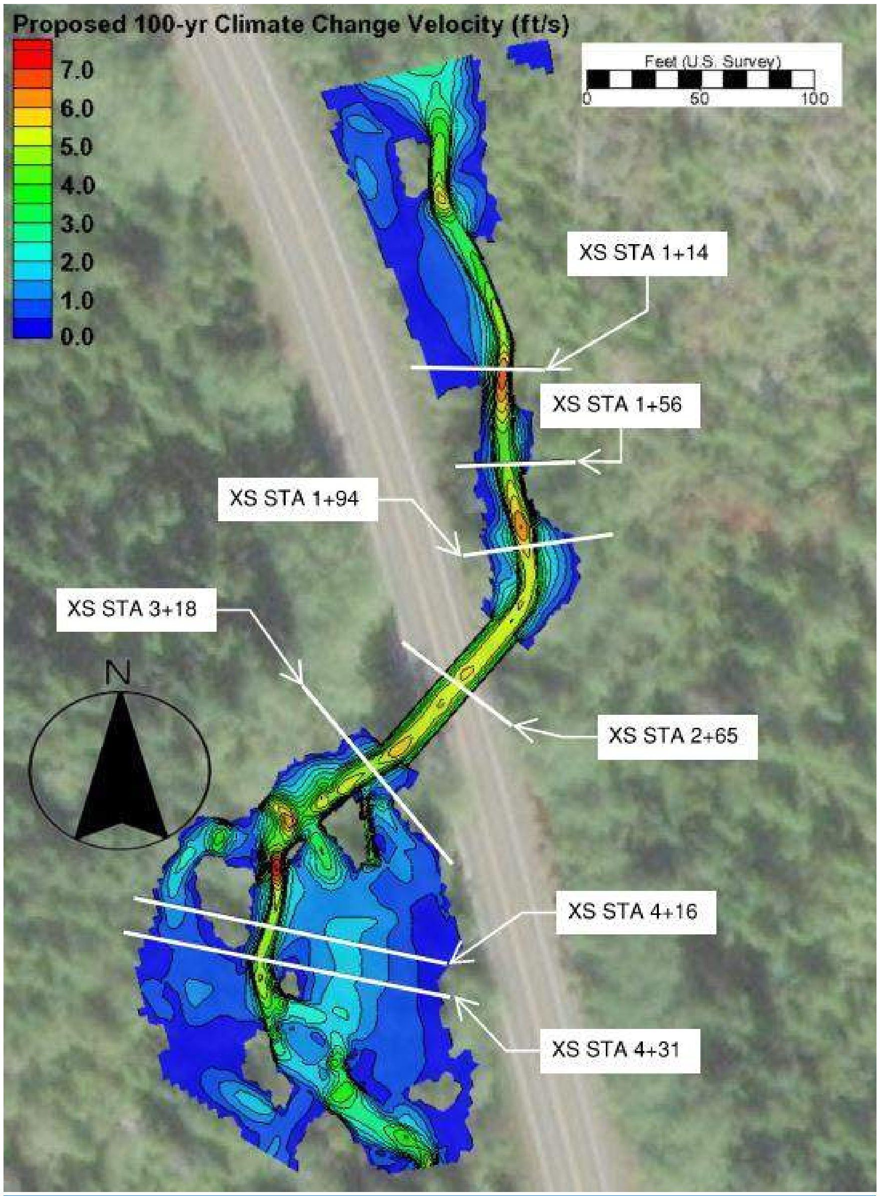


Figure 747~~471~~: Proposed-conditions 2080 predicted 100-year velocity map. Flow direction is from bottom to top of figure.

4.7 Water Crossing Design

Water crossing design for Harlow Creek includes structure type, minimum hydraulic opening width and length, and freeboard requirements.

4.7.1 Structure Type

This PHD Report does not recommend a specific structure type. The layout and structure type will be determined at the FHD phase~~later project phases~~.

4.7.2 Minimum Hydraulic Opening Width and Length

The WCDG recommends sizing the span of the proposed structure based on the agreed-upon BFW, with the span being 1.2 × BFW + 2 feet (WCDG Equation 3.2). Using this equation, along with the modeled BFW of 10.3 feet discussed in Section 2.8.2, results in a structure span of 14.4 feet. Rounding up to the nearest whole foot results in a recommended structure span of 15 feet. ~~The proposed culvert structure is approximately 80 feet in length.~~

Observations from the site visit ~~showed that upstream, flow is pushed into the floodplains as a result o~~indicate that ~~f~~large log jams, formed ~~from~~ by wood from historic logging activities, influence channel form by spreading flood flows across nearby floodplain surfaces. ~~Lateral migration could potentially occur in the upstream reach; however, all flow rejoins the channel at a scour pool upstream of the culvert inlet. As a result, l~~There is not a significant risk of lateral migration ~~is not expected to occur within or around the~~within the upstream reach of the culvert ~~because the flow path in the channel directly upstream of the culvert is well defined~~due to the abundance of large wood accumulations that span the channel corridor and the relatively broad surface that is activated during flood events, coupled with the significant root mass from conifers growing on both banks. Therefore, ~~L~~lateral migration was not accounted for in width determination. This wood also appears to have been stable for long enough for individual pieces to begin to degrade, and debris load is not expected to be a criterion influencing width determination. ~~Additionally, a conservative~~The BFW value ~~was~~ used to determine structure size ~~as field measurements averaged 7.6 feet in the reference reach, but a BFW value of 10.3 feet was used for sizing the minimum hydraulic opening~~accounts for the inset floodplain surfaces expected to be engaged under channel-forming flows. Based on the factors described above, a minimum hydraulic opening of 15 feet was determined to be ~~necessary~~ sufficient to accommodate~~allow for~~ natural processes ~~to occur~~ under the current flow and sediment transport ~~conditions~~regimes. The proposed design, with a 2 percent slope, meets velocity ratio criteria.

A comparison of computed velocities under proposed- and natural-conditions with the current 100-year and predicted 2080 increase in 100-year flows is ~~The projected 2080 100-year flow event was evaluated and the velocity comparisons for these flow rates through the main channel are~~ shown in Table 17~~Table 15~~.

Table 17: Velocity comparison for proposed 15-foot wide structure opening

Location	Proposed conditions			Natural conditions		
	100-Year velocity (ft/s)	2080 predicted 100-Year velocity (ft/s)	Difference (ft/s)	100-Year velocity (ft/s)	2080 ~~predicted~~ ~~100~~predicted 100-Year velocity (ft/s)	Difference (ft/s)
Upstream of structure (XS 3+18.11)	~~4.6~~4.3	~~4.8~~4.5	0.2	~~4.8~~4.6	~~5.2~~4.9	0.3~~4~~
Through structure (XS 2+65.97)	~~6.2~~4.8	~~6.7~~5.1	0.3~~5~~	~~6.1~~4.6	~~6.4~~4.8	0.~~3~~2
Downstream of structure (XS 1+55.83)	~~3.8~~3.9	~~3.9~~4.1	0.2~~1~~	~~3.8~~3.9	~~3.9~~4.1	0.2~~1~~
Velocity ratio	1.1~~3~~	1.1~~4~~		1.0~~3~~	1.0~~2~~	

Note: Velocity ratio calculated as Vstructure/Vupstream.

Velocities in the upstream reach are dampened by the presence of in-channel wood, including logjams, that add flow resistance and encourage multiple flow paths through the main channel and floodplain. This area and the proposed channel, which will be designed to mimic natural roughness, were assigned a Manning's roughness coefficient of 0.06 in the proposed conditions model, while the simplified channel downstream of the culvert was assigned a Manning's roughness coefficient of 0.045.

~~The proposed structure design does not meet the velocity ratio for several reasons. First,in part due to the design slope through the proposed structure that is bis steeper than the downstream reference reach, which increases velocity through the crossing. If the shallower slope of 1.5 percent in from the reference reach downstream of the proposed structure was carried through the proposed grading towardwas extended through the upstream survey extents, it wouldthe proposed grade would not meet the existing ground surface until a point more than 300 feet upstream of the structure. This length of grading was not performed in order to minimizeis not considered to be cost effective and its impacts to the upstream reach, which currently has severa would ldisturb stable log jams and existing habitat features. To avoid grading through these log jams,Proposed grading was therefore extended extendsto a point approximately 15 feet upstream of the proposed structure inlet. As a result, the slope through the structure is steeper than the downstream reach, increasing the velocity through the structure.~~

~~Additionally, the log jams in the upstream reach cause flow to spread across the floodplains. Velocities in the upstream reach are dampened by cross sections have reduced flow within the main channel because of the log jams forcing flow into the floodplains, reducing velocities within the main channelthe presence of in-channel wood, including logjams, that add flow resistance and encourage multiple flow paths through the main channel and floodplain. Flows then reenter the main channel upstream of the structure (immediately downstream of the log jam) and result in increased velocities through the structure when compared to the upstream reach. The channel through the crossing in the natural-conditions model has a lower Manning's roughness n-value and flows straight andis confined within the~~

~~structure confined (i.e.i.e., there is no available floodplain), resulting in elevated velocity compared to the upstream reach.~~

~~Increased velocities under the roadway are not a result of the proposed structure, but of planform, as described above. It is clearThis is exemplified by comparing from viewing the velocities between the natural-conditions model without a structure and the proposed-conditions model with a 15-foot hydraulic opening (Table 18Table 17). The comparison demonstrates that structure size has minimal adverse effect on velocity and that flow is not significantly constricted through the proposed structure, as shown by. C calculating a velocity ratio of 1.0 on the between the results of the natural-conditions model against those of the proposed-conditions model which meets the velocity ratio criteria shows that the velocity ratio meets the criteria (Table 18Table 16).~~

~~Table 18: Velocity comparison for natural conditions and proposed conditions with 15-foot structure~~

~~Parameter~~	~~100-Year velocity (ft/s)~~	~~2080 predicted 100-Year velocity (ft/s)~~	~~Difference (ft/s)~~
~~Proposed-conditions through structure (XS 2+65.97)~~	~~6.2~~	~~6.7~~	~~0.5~~
~~Natural-conditions through structure (XS 2+65.97)~~	~~6.1~~	~~6.4~~	~~0.3~~
~~Velocity ratio~~	~~1.0~~	~~1.0~~	

~~Note: Velocity ratio calculated as Vstructure(proposed)/Vstructure(natural).~~

No size increase was determined to be necessary to accommodate climate resilience~~ since the velocity ratio design criteria is satisfied~~. A minimum hydraulic opening of 15 feet is recommended, and there is no length recommendation for the proposed structure.

4.7.3 Freeboard

The WCDG recommends ~~the~~ that structure designs prevent~~ion of~~ excessive backwater rise and increased main channel velocities during floods that might lead to scour of the streambed and coarsening of the stream substrate, allow the free passage of debris expected to be encountered, and generally suggests a minimum 2 feet of freeboard for streams of this size above the 100-year water surface elevation. WSDOT is incorporating climate resilience in freeboard, where practicable, and has evaluated freeboard at both the 100-year water surface elevation and the projected 2080 100-year water surface elevation.

While the LWM design is conceptual in nature, an additional model run was performed to increase roughness in the channel to reflect anticipated future installation of LWM. Because of the uncertainty of the LWM design, roughness was increased by 0.03 for an additional factor of safety with respect to freeboard. This value represents increased obstructions occupying approximately 15 to ~~-~~50 percent of cross section area (Yochum 2017).

The minimum required freeboard at this location based on BFW was 2 feet at the 100-year flow event. The water depth at the 100-year flow event at the deepest point within the structure is 2.~~2~~1 feet. The 2080 projected 100-year water depth at this point is 2.4 feet. A minimum structure height of 4.4 feet above the thalweg is required to meet the minimum freeboard requirements for the 2080 projected 100-year. If it is practicable to do so, a minimum of ~~5~~ 6 feet between the channel thalweg elevation and inside top of structure is recommended for maintenance and monitoring purposes. The PHD drawings currently assume that ~~5~~ 6 feet of clearance is practicable. If determined not to be practicable during future phases of design, the clearance must be a minimum of 4.4 feet.

Long-term degradation, aggradation, and debris risk were also evaluated at this location. Because the proposed culvert is slightly ~~oversteepened compared to the shallower~~steeper than the downstream reach, the 1.5 percent slope of the downstream reach was carried through the structure and evaluated at the upstream inlet. If the shallower slope of the reference reach was used, the structure inlet would be approximately 1 to 2 feet lower in elevation. Countersinking of the structure will take this into account during the Final Hydraulic Design (FHD) analysis and will include potential future degradation and long-term scour. More information on the risk for long-term degradation and aggradation can be found in Section 8.

4.7.3.1 Past Maintenance Records

As discussed previously in Section 2.4, no maintenance records are available for this crossing.

4.7.3.2 Wood and Sediment Supply

Harlow Creek flows through a heavily wooded basin with a high potential for recruitment, as evidenced within the survey limits. Logging activities have occurred occasionally throughout the basin (Section 2.1), which ~~may reduce the wood supply~~has likely reduced the supply of large stable wood and may increase the sediment supply. It is likely that basin development will remain largely unchanged in the future, with the exception of periodic logging. The large wood transport in this reach is limited by the ~~channel's BFW and heavily wooded banks~~capacity to transport mature trees and by the presence of channel-spanning logjams upstream of the crossing. There ~~was~~ is a ~~high~~ relatively high ~~amount~~density of existing large wood within the channel within the project reach due to historic logging.

Deposition occurred upstream of and around the log jams, indicating a healthy sediment supply in the reach. The proposed increase in structure width will increase flood conveyance and capacity for bedload transport to the downstream reach under channel forming flows, which will benefit habitat conditions through the project reach.

4.7.3.3 Flooding

Though FEMA has not conducted a Special Flood Hazard Area analysis at this site (Section 2.3), the roadway of U.S. 101 does not overtop under existing conditions for any modeled flow event. Backwater is present under all flow conditions, propagating approximately 65 feet upstream. The unnamed roadway heading west off of U.S. 101, however, overtops at both the 100-year and 500-year flow events.

The proposed structure will reduce upstream flooding extents; according to the model and flow results outlined in Section 4.6, the unnamed roadway will no longer overtop at any of the modeled flow events.

As the unconfined channel converges at the inlet of the structure, a pool forms, but no backwater is present in the stream reach under the proposed conditions.

4.7.3.4 Future Corridor Plans

There are currently no long-term plans to improve U.S. 101 through this corridor.

4.7.3.5 Impacts

It is not anticipated that the road level will be raised to accommodate the proposed minimum hydraulic opening. A final decision will be made at a later design phase.

4.7.3.6 Impacts to Fish Life and Habitat

In discussion with WDFW and the ~~tribes~~Tribe, it is expected that the proposed minimum hydraulic opening of ~~5~~ 15 feet will not result in ~~no~~ substantial detrimental impacts to fish life and habitat.

5 Streambed Design

During the site visit, streambed sediment size was observed at the site and used to create a design sediment size for the proposed grading.

5.1 Bed Material

The proposed bed material gradation was created using standard WSDOT specification material~~ to mimic the gradation documented in the pebble count as closely as possible~~. The proposed mix will consist of ~~50~~230 percent~~%~~ streambed sediment, ~~25~~5~~% 4-inch cobbles, and 25% 6-inch cobbles, 30% 8-inch cobbles, 25% 10-inch cobbles, and 15~~40 percent ~~12~~6-inch cobbles, and 30 percent~~%~~ 10~~-inch~~-inch~~”~~ cobble~~ because the observed material was made up of a mixture of gravels and cobbles~~. A comparison of the ~~(~~reference reach pebble count~~)~~~~observed~~ and proposed streambed material size distribution is provided in Table 19~~Table 17~~. When comparing the observed and proposed sediment sizes, it is relevant to remember that the reference reach has slightly lower slope (1.5 percent~~%~~) than the design reach (2.0 percent~~%~~). Because there is a risk of near-term washout of the sediment and entrainment of fines within the structure if the observed gradation is used, we recommend a slightly coarser proposed mix for this location (D_{50} of 2.0 inches as opposed to an observed D_{50} of 1.3 inches). The goal of the design team was that the D_{50} should be stable at a 2-year event to prevent excessive loss of material from the culvert during the first few storm seasons, while the material develops a natural armor layer, and the system has an opportunity to respond to the geomorphic effects of the design LWM.

Table 18~~19~~: Comparison of observed and proposed streambed materials

Sediment Size	Observed Diameter (in)	Proposed Diameter (in)	Meander Bar Diameter (in)
D_{16}	0.4	0.~~1~~86	0.6
D_{50}	1.3	~~1.3~~~~2.1~~2.0	3.3
D_{84}	2.9	~~2.9~~~~6.8~~5.4	13.2
D_{95}	4.0	~~5.0~~~~9.4~~8.3	16.5
D_{100}	10.1	~~6.0~~~~12.0~~10.0	18.0

The Modified Critical Shear Stress Approach (as described in Appendix E of the United States Forest Service [USFS] Guidelines) was used to analyze mobility for the proposed streambed material at the project site (USFS 2008). The sediment mobility analysis indicates that for the observed gradation, ~~all~~ only material sizes larger than the D_{84} ~~will~~would be stable at the 2-year event and all material sizes ~~smaller than the D84 are anticipated to~~would ~~move~~ mobilize at the ~~2~~100-year flow~~ and higher~~. ~~At the time of the site visit, sediment supply within the system appeared to be healthy. Because of this healthy sediment supply and the size similarity between observed and proposed materials, mobility of this material is not a concern.~~ ~~For this site, we see~~~~There is a risk of near-term washout of the sediment and entrainment of fines from within the culvertstructure if thisthe observed gradation is used~~The proposed gradation is designed such that the large~~st~~r material (D~~84~~$_{50}$ and larger) will provide a degree of stability for smaller material, while still being deformable at the 2-year event. The D_{50} was selected as the threshold for stability at the 2-year event to prevent too large a fraction of the material in the culvert from mobilizing at a ~~very~~relatively frequent interval and to reduce the risk of localized streambed degradation and bed coarsening~~., because the gravels are mobile at low storm events, and given the proposed conditions hydraulics~~. ~~The observed gradation is completely mobile (through the D100) at the 2-year event, which underscores the risk of washout within the channel grading limits.~~ In addition, the sediment input from upstream is expected to be low in the foreseeable future, as evidenced by the ~~significant amounts~~number of full-spanning logging debris jams and the predominantly fine materials ~~evidient~~evident within the upstream channel. Meander bars are included to control channel shape and initiate stream structure. The bars are composed of well-graded streambed material that is between 1 and 2 times the D_{100} of the existing streambed mix. The meander bar mix is composed of 30 percent streambed sediment, 50 percent 10-inch streambed cobble, and 20 percent 1-man streambed boulders. The meander bar mix is stable at the D_{50} and above for the 2-year event and at the D_{84} and above for the 100-year flow event. ~~Two options for managing this risk include coarsening the substrate mix or adding coarse barsbands to retain gravels within the culvert and create a step-pool morphology within the culvert. To maximize the potential habitat value in the culvert, we recommend using coarse barsbands to create steps within the culvert profile,within the structure and backfilling between these with the gravel mix shown above. The proposed gradation is designed such that the largest sized material (D84 and larger) will provide a degree of stability for smaller material, while still being deformable, at the 2-year event.~~ See Appendix D for streambed sizing and sediment mobility calculations.

5.2 Channel Complexity

To encourage a complex channel that is more habitable for fish, a design including both LWM and non-LWM structures was developed.

5.2.1 Design Concept

~~gently stream planform upstream and downstream of the around the~~The LWM concept is first based on an approach of incorporating wood within the entire channel cross-section, including within the channel bed, within the active low-flow channel and as overhead cover above the channel invert. Secondly the approach is to use a whole tree when harvesting a rootwad log. This "whole tree" design approach is based first on identifying the diameter and length of the rootwad log needed, then incorporating the remaining pieces of the tree that can be created from the harvest of that tree. During final design, it will be illustrated how to incorporate the slash and branches from the harvest of the tree, such that the whole tree is used in the project site, rather than leaving significant waste / slash piles at the harvest site. The layout below is the conceptual orientation of a series of structures intended to initiate local channel evolution of complex instream habitat, including lateral scour to increase thalweg sinuosity and decrease overall channel slope (Figure 75~~Figure 72Figure 74~~). This complex matrix of wood will provide very high hydraulic roughness, reducing stream power and generating low-velocity refuge areas in the channel during storm flows.

The 75th percentile of key piece density in accordance with Fox and Bolton (2007) and Chapter 10 of the *Hydraulics Manual* recommend 3.4 key pieces and 39.48 cubic yards of volume per 100 feet of channel. This percentile of wood placement is suggested. ~~to compensate for cumulative deficits of wood~~

~~loading due to future potential development.~~ A conceptual LWM layout based on the assumption of a buried structure has been developed for this project area and is provided in Figure 72~~Figure 71; a similar conceptual LWM layout based on the assumption of a bridge structure is provided in Figure 72~~. The conceptual layout proposes ~~12~~ 22 key pieces in a 145.5-foot-long project reach (including the structure length), yielding ~~8.2~~15.2 key pieces per 100 feet of linear channel length. This satisfies and exceeds the Fox and Bolton (2007) 75th percentile criterion ~~by~~ with a total key piece loading of ~~141~~ 440 percent of target. The conceptual layout exceeds total LWM volume target by approximately 7 percent.

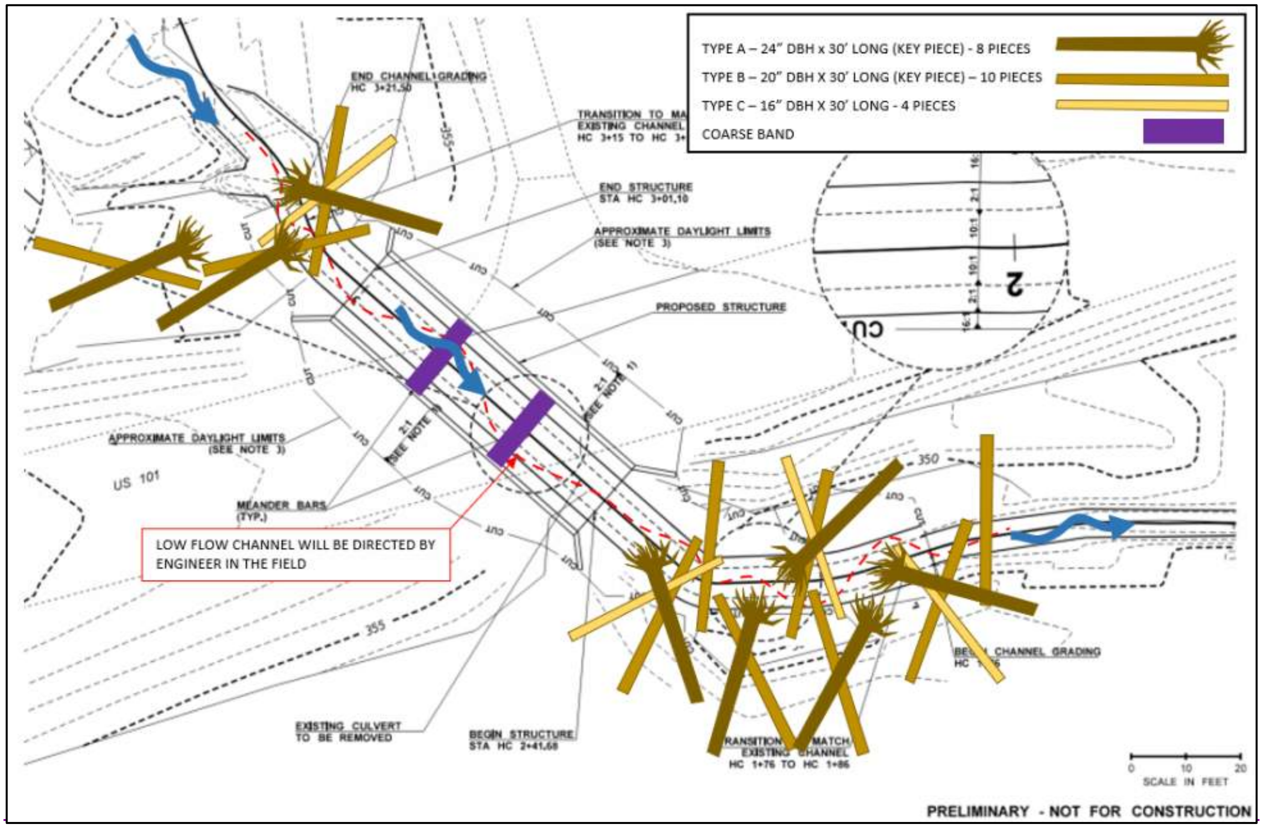
~~Some mobile wood may be placed downstream of the culvert.~~ Wood structures placed in the stream will serve as habitat features for fish, ~~and those placed along the outside of bends are to form pools at the outside of the bends underneath the rootwad structures. Wood in the floodplains also serve as habitat features for fish, particularly under high flow conditions. Preformed scour pools are recommended at points in the channel where rootwads are interacting with flow~~add hydraulic complexity, and increase the stream's ability to sort and retain gravels useful for fish habitat. The complex wood matrix will provide beneficial geomorphic and habitat function; providing multiple flow paths through and around the structure where minor channel bed and bank deformation is encouraged, while dissipating flow energy at higher flows. Arranging logs in typical clusters that alternate along streambanks provides an intentional meandering of the main channel thalweg, while increasing the efficiency and repeatability of wood placement during construction.

A key component of the conceptual design is that wood pieces will be oriented at varying degrees of pitch angle (horizontal) to provide flow-through paths above and below the logs, and to avoid formation of a "weir" effect in the long term. Additionally, wood pieces will be oriented at varying angles relative to streamflow (longitudinally) so there is adequate space for the channel to form pools and buildup of sediment deposits. Wood will be installed ~~at or under the water table~~both within the low-flow channel and within the floodplain area to increase its engagement with flow at all conditions~~, which is beneficial for fish but also maintains a low profile to not increase risk of flooding~~ to provide refuge areas during storm flows. The majority of wood will be placed downstream of the crossing ~~to hold proposed channel grade in the long term~~as significant wood already exists upstream of the culvert inlet. ~~Under~~ Within the crossing structure, ~~meander barbs~~coarse ba~~rs~~nds will span perpendicular to flow and installed in a concave shape ~~be used to~~ to retain gravels, create channel complexity and encourage a low flow notch to develop ~~with~~through natural processes. Wood stability will be assessed at the FHD level; at this time, anchoring is not anticipated. During the FHD, an analysis will be performed to determine at which flows the mobile wood in the stream becomes mobile.

Risk of fish stranding during summer flow conditions is minimal because a continuous meandering thalweg is anticipated to develop, winding between scour pools generated by the hydraulics of storm flows interacting with the rootwads.~~in the floodplainoutside of the channel margin if adjacents habitat units were to dry up. avoid predationprotect themselves~~

~~Non-LWM structures being recommended are coarse bands barbs within the structure. These barbs create channel complexity by deflecting the low flow around the barbs, similar to how rootwads on LWM interact with the channel.coarse bands will create a diverse flow profile of steps and pools within the culvert.~~

No special design considerations should be made.



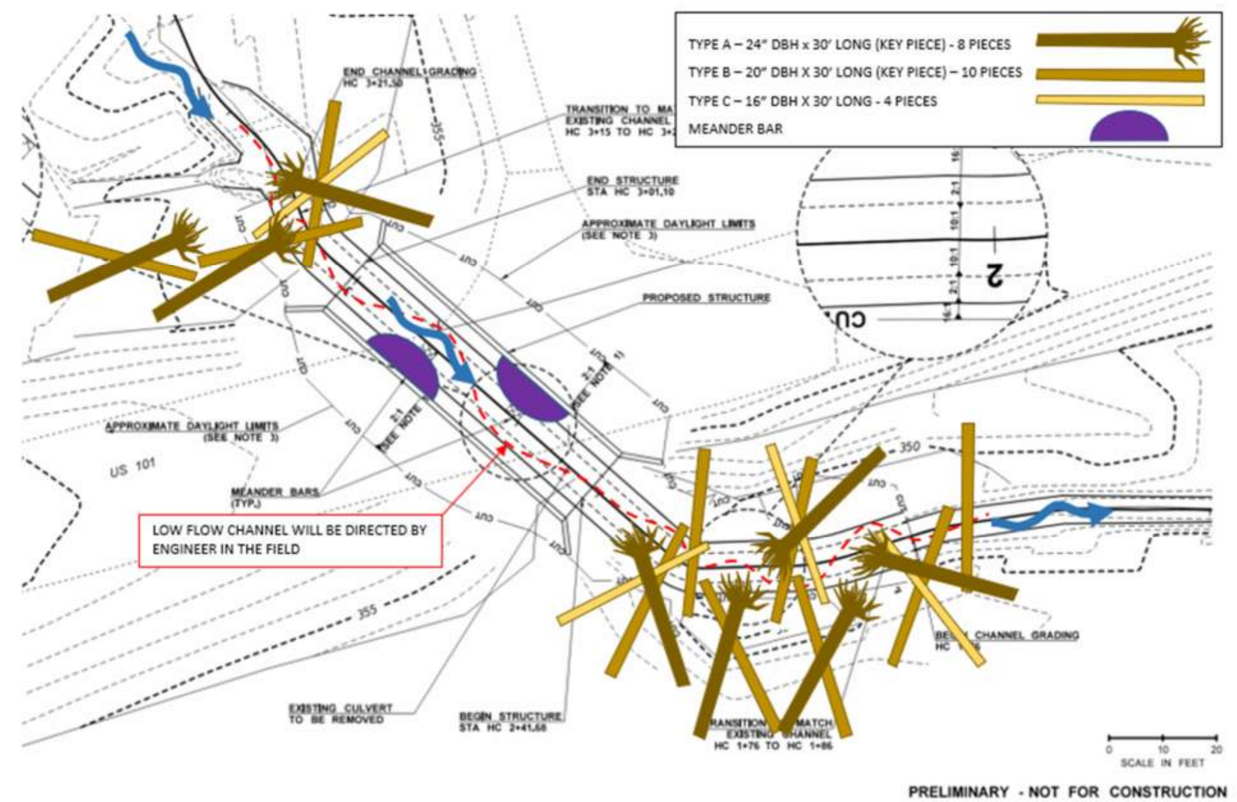


Figure 75~~75~~72: Conceptual layout of habitat complexity ~~assuming buried structure~~

6 Floodplain Changes

No FEMA flood hazard analysis was ~~performed at~~available for this location (Section 2.3). The pre-project and expected post-project conditions were evaluated to determine whether there would be a change in water surface elevation and floodplain storage.

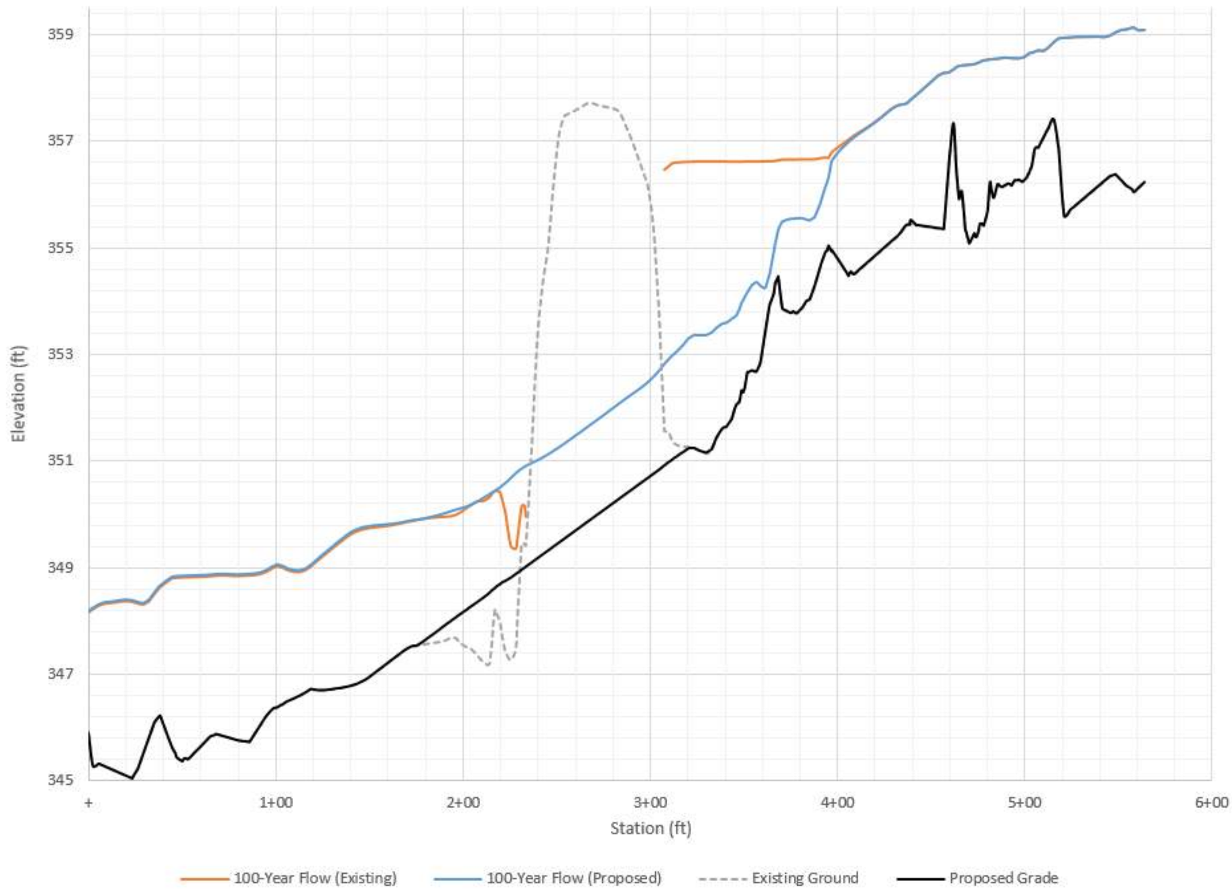
6.1 Floodplain Storage

Floodplain storage is anticipated to be significantly impacted by the proposed structure. The installation of a larger hydraulic opening will reduce the amount of backwater and associated peak flow attenuation that was being provided by the smaller, existing culvert. A comparison of pre- and post-project peak flow events was not quantified as the models were run with a ~~steady~~ constant flow rate specified at the upstream boundary of the model, ~~–~~ therefore only the peak discharge of flood events was evaluated~~.~~. An unnamed road heading west off of U.S. 101 will no longer be overtopped after installation of the proposed structure and, as a result, secondary flow from Harlow Creek will no longer enter road drainage on the west side of U.S. 101. All flow will remain with the channel.

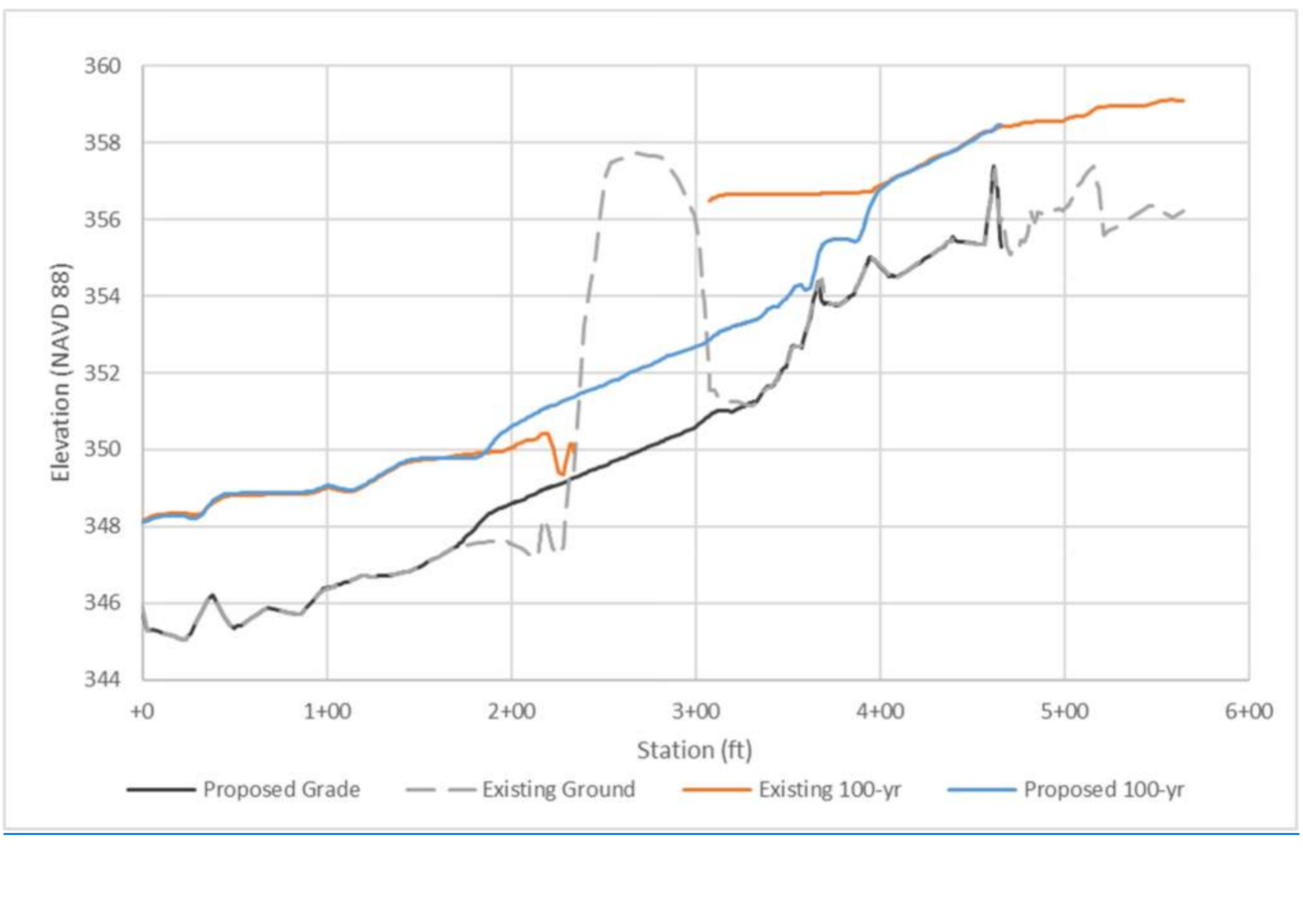
6.2 Water Surface Elevations

Installation of the proposed structure would eliminate the backwater impacts just upstream of the existing culvert, resulting in a reduction in water surface elevation upstream. The water surface elevation is reduced by as much as 3.6 feet at the inlet of the existing culvert at the 100-year event as shown in Figure 73~~Figure 73~~ and Figure 74~~Figure 74~~. Figure 74~~Figure 74~~ also depicts the extent of backwater and the overtopping of the unnamed roadway heading west off of U.S. 101 that is eliminated.

Immediately downstream of the culvert, channel regrading for proposed conditions causes a rise by as much as 1.~~4~~9 feet in water surface near STA 2+28. The local water surface rise is a result of the fill in the scour hole downstream of the existing culvert outlet. Past the outlet, the water surface change varies between no change and less than a 0.1-foot rise from the existing to proposed conditions.

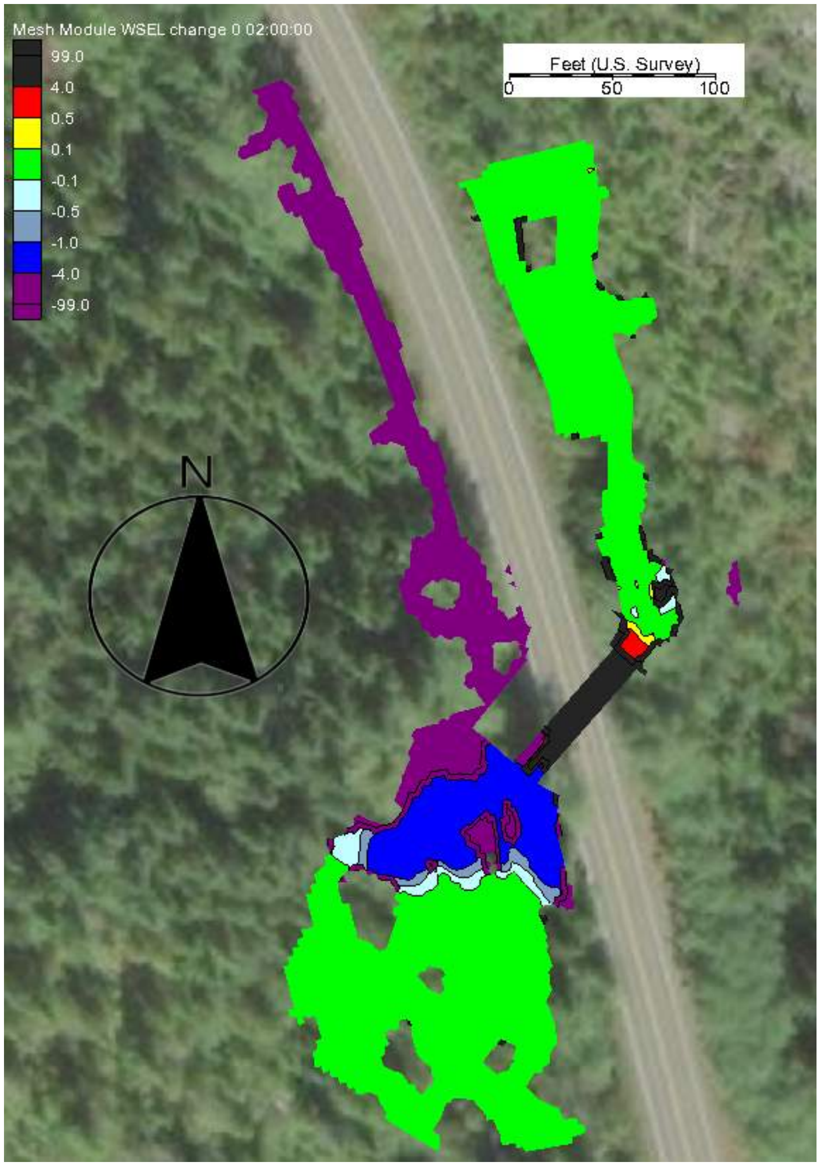


359
357
355
353
351
349
347
345
Elevation (ft)
+
1+00
2+00
3+00
4+00
5+00
6+00
Station (ft)
100-Year Flow (Existing)
100-Year Flow (Proposed)
Existing Ground
Proposed Grade



360
358
356
354
352
350
348
346
344
Elevation (NAVD 88)
+0
1+00
2+00
3+00
4+00
5+00
6+00
Station (ft)
Proposed Grade
Existing Ground
Existing 100-yr
Proposed 100-yr

Figure 76~~7673~~: Existing and proposed 100-year water surface profile comparison


Mesh Module WSEL change 0 02:00:00
99.0
4.0
0.5
0.1
-0.1
-0.5
-1.0
-4.0
-99.0
Feet (U.S. Survey)
0
50
100
N

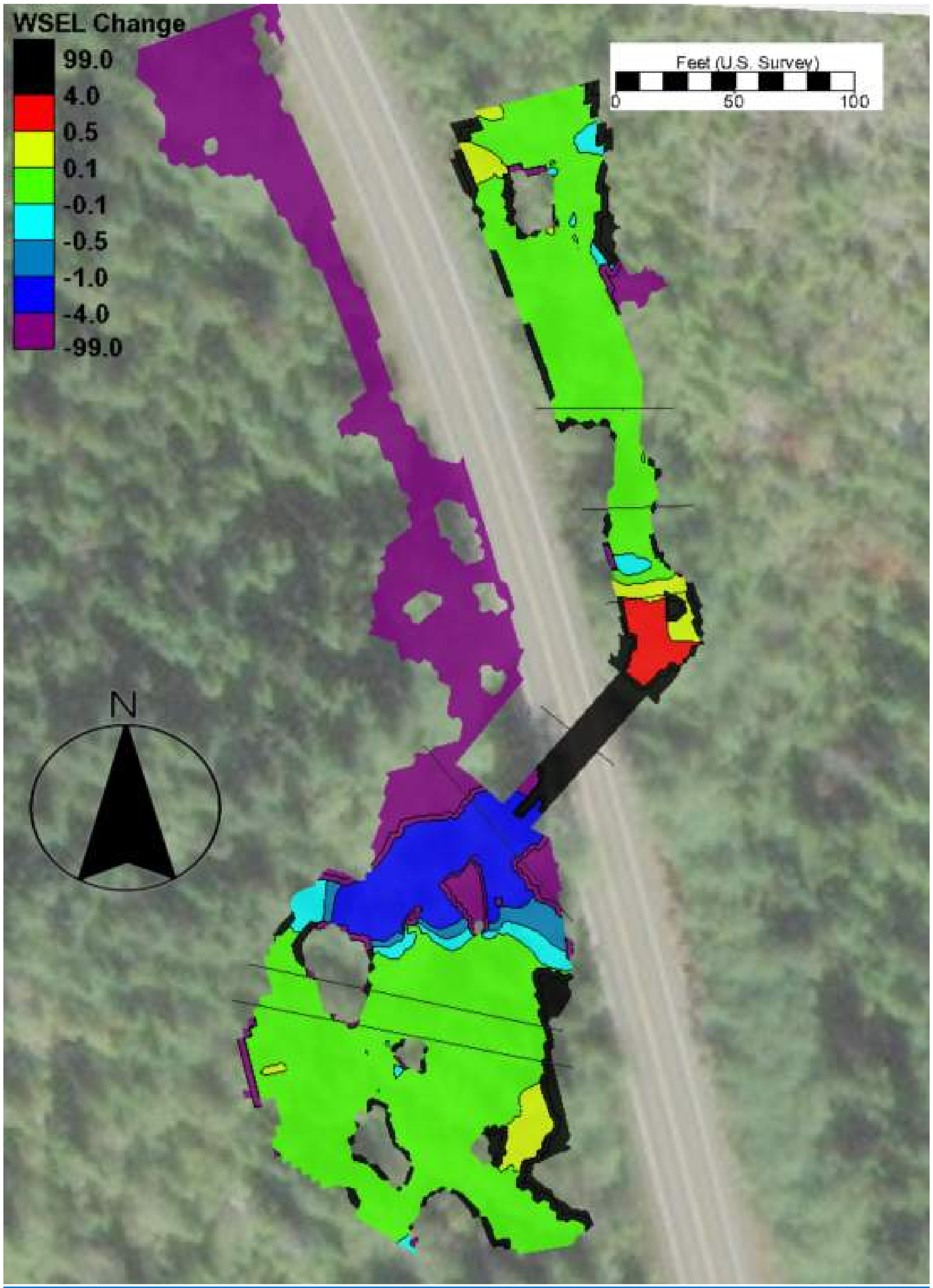


Figure ~~77~~~~77~~74: 100-year water surface elevation change. Flow direction is from bottom to top of figure.

In Figure 74~~Figure 74~~, positive values indicate an increase in water surface elevation from existing to proposed conditions. Black represents new water surface extents and purple represents water surface extents that have been removed.

7 Climate Resilience

WSDOT recognizes climate resilience as a component of the integrity of its structures and approaches the design of bridges and buried structures through a risk-based assessment beyond the design criteria. For bridges and buried structures, the largest risk to the structures will come from increases in flow and/or sea level rise. The goal of fish passage projects is to maintain natural channel processes through the life of the structure and maintain passability for all expected life stages and species in a system.

7.1 Climate Resilience Tools

WSDOT also evaluates crossings using the mean percent change in 100-year flood flows from the WDFW Future Projections for Climate-Adapted Culvert Design program. All sites consider the 2080 mean percent increase throughout the design of the structure. Appendix I contains the information received from WDFW for this site.

7.2 Hydrology

For each design WSDOT uses the best available science for assessing site hydrology. The predicted flows are analyzed in the hydraulic model and compared to field and survey indicators, maintenance history, and any other available information. Hydraulic engineering judgment is used to compare model results to system characteristics; if there is significant variation, then the hydrology is reevaluated to determine whether adjustments need to be made, including adding standard error to the regression equation, basin changes in size or use, etc.

In addition to using the best available science for current site hydrology, WSDOT is evaluating the structure at the 2080 predicted 100-year flow event to check for climate resilience. The design flow for the crossing is 91.1 cfs at the 100-year storm event. The projected increase for the 2080 flow rate is 24.2 percent, yielding a projected 2080 flow rate of 113.2 cfs.

7.3 Climate Resilience Summary

A minimum hydraulic opening of 15 feet and a minimum low chord elevation of ~~5~~ 6 feet above the thalweg allows for the channel to behave similarly through the structure as it does in the adjacent reaches under the projected 2080 100-year flow event. This will help to ensure that the structure is resilient to climate change and the system is allowed to function naturally, including the passage of sediment, debris, and water in the future while accommodating WSDOT Maintenance clearance.

8 Scour Analysis

Total scour will be computed during later phases of the project using the 100-year, 500-year, and projected 2080 100-year flow events. The structure will be designed to account for the potential scour at the projected 2080 100-year flow events. For this phase of the project, the risk for lateral migration and potential for degradation are evaluated on a conceptual level. This information is considered preliminary and is not to be taken as a final recommendation in either case.

8.1 Lateral Migration

Channel migration was assessed by using historical imagery and modeling results. The historical aerial imagery gives little information on channel migration near the project site because the channel is in a forested area, making it difficult to decipher where the channel is in each aerial.

Observations from the site visit showed that upstream, flow is pushed into the floodplains as a result of large log jams formed from historic logging activities. Lateral migration could potentially occur in the upstream reach; however, all flow rejoins the channel at a scour pool upstream of the culvert inlet. As a result, lateral migration is not expected to occur within or around the culvert because the flow path in the channel directly upstream of the culvert is well defined. Lateral migration was not accounted for in width determination.

8.2 Long-term Aggradation/Degradation of the Riverbed

There is a risk of degradation based on the proposed channel grading. The slope of the culvert, 2.~~6~~ 0 percent, is steeper compared to the slope of the downstream reach, 1.5 percent. As a result, ~~lengthening~~ extending the downstream slope of 1.5 percent through the culvert reveals that there is a potential for 1 to 3 feet of long-term degradation.

Summary

Table 20~~Table 18~~ presents a summary of this PHD Report results.

Table 19~~20~~: Report summary

Stream crossing category	Elements	Values	Report location
Habitat gain	Total length	3,600'	2.4 Site Description
Bankfull width	Average BFW	10.3'	2.8.2 Channel Geometry~~Channel Geometry~~
	Reference reach found?	Y	2.8.1 Reference Reach Selection~~Reference Reach Selection~~
Channel slope/gradient	Existing crossing	2.8%	2.8.4 Vertical Channel Stability~~Vertical Channel Stability~~
	Reference reach	1.5%	2.8.2 Channel Geometry~~Channel Geometry~~
	Proposed	2.~~6~~0%	4.4.2 Channel Planform and Shape~~Channel Planform and Shape~~
Countersink	Proposed	FHD	4.7.3 Freeboard~~Freeboard~~
	Added for climate resilience	FHD	4.7.3 Freeboard~~Freeboard~~
Scour	Analysis	See link	8 Scour Analysis ~~Scour Analysis~~
	Streambank protection/stabilization	See link	8 Scour Analysis ~~Scour Analysis~~
Channel geometry	Existing	See link	2.8.2 Channel Geometry~~Channel Geometry~~
	Proposed	See link	4.4.2 Channel Planform and Shape~~Channel Planform and Shape~~
Floodplain continuity	FEMA mapped floodplain	N	6 Floodplain Changes~~Floodplain Changes~~
	Lateral migration	~~Y~~N	2.8.5 Channel Migration~~Channel Migration~~
	Floodplain changes?	Y	6 Floodplain Changes~~Floodplain Changes~~
Freeboard	Proposed	2'	4.7.3 Freeboard~~Freeboard~~
	Added for climate resilience	Y	4.7.3 Freeboard~~Freeboard~~
	Additional recommended	1.6~~0.2~~'	4.7.3 Freeboard~~Freeboard~~
Maintenance clearance	Proposed	~~5'~~6'	4.7.3 Freeboard~~Freeboard~~
Substrate	Existing	TBD	2.8.3 Sediment~~Sediment~~
	Proposed	TBD	5.1 Bed Material~~Bed Material~~
Hydraulic opening	Proposed	15'	4.7.2 Minimum Hydraulic Opening Width and Length~~Minimum Hydraulic Opening Width and Length~~

	Added for climate resilience	N	4.7.2 Minimum Hydraulic Opening Width and Length~~Minimum Hydraulic Opening Width and Length~~
Channel complexity	LWM	Y	5.2 Channel Complexity~~Channel Complexity~~
	Meander bars	Y	5.2 Channel Complexity~~Channel Complexity~~
	Boulder clusters	N	5.2 Channel Complexity~~Channel Complexity~~
	Mobile wood	Y	5.2 Channel Complexity~~Channel Complexity~~
Crossing length	Existing	74'	2.7.2 Existing Conditions~~Existing Conditions~~
	Proposed	See link~~74'~~	4.7.2 Minimum Hydraulic Opening Width and Length~~Minimum Hydraulic Opening Width and Length~~
Floodplain utilization ratio	Flood-prone width	81.6	4.4.1 Existing-Conditions Model Results~~Existing-Conditions Model Results~~
	Average FUR upstream and downstream	11.1/3.1	4.4.1 Existing-Conditions Model Results~~Existing-Conditions Model Results~~
Hydrology/design flows	Existing	See link	3 Hydrology and Peak Flow Estimates~~Hydrology and Peak Flow Estimates~~
	Climate resilience	See link	3 Hydrology and Peak Flow Estimates~~Hydrology and Peak Flow Estimates~~
Channel morphology	Existing	See link	2.8.2 Channel Geometry~~Channel Geometry~~
	Proposed	See link	5.2 Channel Complexity~~Channel Complexity~~
Channel degradation	Potential?	Y	8.2 Long-term Aggradation/Degradation of the Riverbed~~Long-term Aggradation/Degradation of the Riverbed~~
	Allowed?	Y	8.2 Long-term Aggradation/Degradation of the Riverbed~~Long-term Aggradation/Degradation of the Riverbed~~
Structure type	Recommendation	N	4.7.1 Structure Type~~Structure Type~~
	Type	NA	4.7.1 Structure Type~~Structure Type~~

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Appendices

Appendix A: FEMA Floodplain Map (not used)

Appendix B: Hydraulic Field Report Form

Appendix C: SRH-2D Model Results

Appendix D: Streambed Material Sizing Calculations

Appendix E: Stream Plan Sheets, Profile, Details

Appendix F: Scour Calculations FHD ONLY (to be completed at FHD)

Appendix G: Manning's Calculations (not used)

Appendix H: Large Woody Material Calculations ~~(to be completed at FHD)~~

Appendix I: WDFW Future Projections for Climate-Adapted Culvert Design

Appendix J: Bundle 3 Comment Response Plan

Appendix A: FEMA Floodplain Map

This appendix was not used because no analysis was ~~performed by~~available from FEMA in this crossing's location.

Appendix B: Hydraulic Field Report Form

Appendix C: SRH-2D Model Results

Appendix D: Streambed Material Sizing Calculations

Appendix E: Stream Plan Sheets, Profile, Details

Appendix F: Scour Calculations

This appendix was not used because it is used for the FHD Report, not the PHD Report.

Appendix G: Manning's Calculations

This appendix was not used because Manning's calculations were not needed to support the values chosen.

Appendix H: Large Woody Material Calculations

~~This appendix was not used because it is used for the FHD Report, not the PHD Report.~~

Appendix I: Future Projections for Climate-Adapted Culvert Design

Appendix J: Bundle 3 Comment Response Plan